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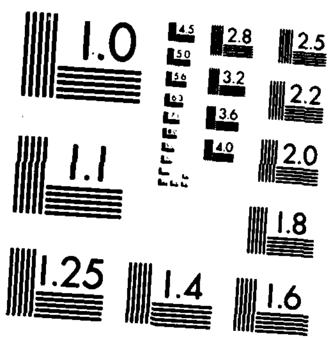

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EFFECT OF FUEL PROPERTIES ON INJECTION CHARACTERISTICS OF FOUR DIFFERENT DIESEL INJECTION SYSTEMS

INTERIM REPORT
BFLRF No. 210

By

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Four diesel injection systems were selected for evaluating the effects of fuel properties on diesel spray characteristics. The selected injection systems were from the following Navy engines: the Detroit Diesel Allison 4-53T, the Detroit Diesel Allison 4-71TI, the Cummins NH-220, and the Westerbeke 4-108. Fuel properties which were examined were viscosity and specific gravity. The injection systems were operated on nine test fuels covering a broad range of viscosity and specific gravity. High-speed movies were taken of the fuels being injected into a high-pressure environment. Penetration and cone angle data were reduced from the movies and used as a basis for fuel-to-fuel comparisons. In addition, drop size distribution were obtained for the Westerbeke 4-108 injection system operating on four fuels with different viscosities.

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FOREWORD

This report was prepared at the Belvoir Fuels and Lubricants Research Facility (SwRI), Southwest Research Institute, under DOD Contract Nos. DAAK70-82-C-0001 and DAAK70-85-C-0007. The project was administered by the Fuels and Lubricants Division, Materials, Fuels and Lubricants Laboratory, U.S. Army Belvoir Research, Development and Engineering Center, Fort Belvoir, Virginia 22060-5606, with Mr. F.W. Schaekel, STRBE-VF, serving as Contracting Officer's Representative. This program was funded by the David Taylor Naval Ship Research and Development Center with Mr. R. Strucko, Mobility Fuels Group, Code 2759, serving as Technical Monitor. This report covers the period of performance from October 1983 to December 1985.

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I. INTRODUCTION

Diesel engine fuel injection systems are designed to inject fuel into the combustion chamber in a precise and consistent manner. System requirements include precise fuel metering, accurate injection timing, control of the proper rate of injection, proper spray pattern and fuel atomization for the given engine, and sharp beginnings and endings of injection. Control of the above parameters is essential in preventing misfire, surge or overfueling, engine knock, smoking, deposition, and lube oil contamination. In most combustion chamber designs, the fuel injection system must propel the fuel into the air to provide for good atomization but must not allow impingement of the fuel on surfaces within the combustion chamber. Contaminated, emergency, alternative, and other off-specification fuels may have properties which cause degradation of the injection process and, in turn, adversely affect the engine performance. The fuel properties which affect the performance of a given injection system include viscosity, specific gravity, and surface tension. The injector performance is generally measured in terms of penetration rate and cone angle.

Many computer models and empirical correlations have been developed to predict penetration and cone angle as functions of time with variations in fuel properties and nozzle designs. Major work recently done in this area can be classified in three groups: multidimensional modeling, phenomenological modeling, and empirical solution methods.

Multidimensional computer models involve numerically solving the conservation of mass, momentum and energy equations. They have little dependence on experimental data, but require substantial computing effort to obtain results. Examples of this type of approach are: 1) The CONCHAS-SPRAY program at Los Alamos National Lab; 2) the RPM-SPRAY program done by Gosman; 3) work done by Bracco and Associates (1972-1976) (1)*; and, 4) the work of Hiraki and Rife.(2) Through this work, some insight was gained into the interaction of liquid inertia, surface tension, and aerodynamic effects which leads to liquid atomization.

* Underscored numbers in parentheses refer to the list of references at the end of this report.

Another approach to modeling diesel sprays, termed the phenomenological approach, involves using the computer to solve simplified equations of spray formation, air entrainment, and combustion phenomena. Generally, this approach requires much less computing effort, but the simplified equations depend heavily on experimental data, and apply only to restricted types of problems. Dent used one such model in a specific diffusion combustion situation, where he was able to define a structure of turbulence.(2) Singh, et al. (3) present a model numerically solving mass and momentum equations as in the multidimensional cases, but they used empirical equations for evaporation rate and drag force, and modeled only injections into quiescent air. The Singh model might be considered a mixture of multidimensional and phenomenological approaches.

The least general of the diesel spray model approaches involves simply using experimental data to correlate spray tip penetration as a function of time, while using jet disintegration theory to predict the effect of fuel properties and nozzle design. Hay and Jones (4) reviewed several correlations previous to 1972, and found that the Schweitzer (5), Wakuri (6) and Dent (7) correlations, which show penetration proportional to square root of time, seem to be the most accurate.

Rife and Heywood (8) later proposed that penetration is directly proportional to time as long as the jet is continuous, and then varies as the square root of time. Hiroyasu (9) elaborated on that idea by defining a jet breakup length to distinguish the two possible regions, and came up with correlations for each. One slightly different approach was that of Harrington.(10) He used spray penetration data to correlate spray tip acceleration rather than the penetration itself and was thus able to obtain better accuracy in tip acceleration and velocity results than those who correlated penetration and tried to differentiate with respect to time.

Thus, researchers have used full-scale multidimensional models to understand the effects of various fuel spray parameters, phenomenological models to attempt solutions of practical diesel spray situations, and empirical correlations to obtain accurate prediction of fuel spray penetration in specific situations. From the work of previously mentioned researchers, the following observations can be made about those quantities which might affect fuel spray formation:

1. Penetration tends to increase with pressure drop across the nozzle and with nozzle diameter, while decreasing with an increase in gas density. This is demonstrated in Hiroyasu's correlations, shown below, which are in the same form as several other correlations, and which agree well with experimental data.(9)

$$S = 0.39\sqrt{\frac{2\Delta P}{\rho_a}}\, t \qquad t < t_b$$

$$S = 2.95\left(\frac{\Delta P}{\rho_a}\right)^{1/4} \sqrt{Dt} \qquad t \geq t_b$$

Where:

S = Tip penetration
ΔP = Pressure drop across the nozzle
t = Time
$t_b = 28.65 \dfrac{\rho_\ell D}{\sqrt{\rho_a \Delta P}}$
$\rho\ell$ = Density of liquid
ρa = Density of gas
D = Nozzle orifice diameter

Singh (3) also compares his mathematical model results to the above correlation, and found they match closely, so apparently it is a good representation of the effects of ΔP, ρ_a and D.

2. In general, for a constant flow rate of fuel those factors which increase penetration also tend to decrease cone angle. Logically, a more streamlined jet with a small cone angle, less aerodynamic drag, and a smaller cross-sectional area would penetrate faster. One example of this is shown below in another of Hiroyasu's correlations;(3)

$$\text{Cone angle } \Theta = 0.05\left(\frac{\rho_a \Delta P D^2}{\mu_a^2}\right)^{1/4} \qquad \mu_a = \text{viscosity of air}$$

Comparing this equation to the equation for penetration shows that ΔP and D (which directly determine flow rate), have similar effects on cone angle and penetration while the gas density has a completely inverse effect. Viscosity of the liquid is one parameter not included in most existing correlations for penetration. Edsell (11) did show, however, that a vegetable oil with thirteen times the viscosity of diesel fuel penetrated farther and had narrower cone angles.

3. Nozzle design has a significant effect on cone angle and penetration because it directly determines the fuel flow rate, direction, and degree of turbulence. The complex interactions going on make it difficult to compare nozzle design features using experimental data, but Reitz and Bracco (12) were able to show that orifice inlet sharpness increases cone angle, while Hiroyasu (3) presented data showing that orifice length causes cone angle to increase to a maximum and then decrease.

It is apparent from the literature that several spray models exist. Unfortunately, application of these models is limited to very specific and well-defined injection systems. Also the availability of information regarding the effects of fuel properties on the injection characteristics is limited. The objective of this program was to determine the effects of fuel properties on the spray characteristics of Navy high-speed diesel fuel injection equipment. Since this program involved investigation of four different injection systems of significantly different design, the more empirical method of analyzing the results was adopted. Basically for each injection system, fuel property effects were determined by comparing penetration and cone angle data for each fuel.

II. SCOPE

A. High-Speed Diesel Injection Systems

The injection systems selected for this program were based upon a survey of high-speed diesel engines in the Navy's inventory, Table 1. Four engines and their corresponding injection systems were identified as being representative of approximately 90 percent of the Navy's inventory. These engines are the Detroit

TABLE 1. INVENTORY OF NAVY HIGH-SPEED DIESEL ENGINES

Engine Type	Units*	Injection Type
DDA/71 series	1028	DDA
DDA/149 series	82	DDA
DDA/53 series	135	DDA
Waukesha/L1616DSIN	21	Modified DDA
Waukesha/L161DN	2	Modified DDA
Hercules/DFXD	35	Bosch APE, Pintle
Hercules/DFXE	2	Bosch APE, Pintle
Cummins/NH-220	52	Cummins PT
Cummins/VA3000M	2	Cummins PT
MTU/8V331TC80	12	ND**
Buda/6LD468	2	ND
Westerbeke 4-107/4-108	351	CAV, Pintle
Gray/4D129	8	ND
Gray/6D427	6	ND

* Taken from "Navy Shipboard Fuels Flexibility Program Task A," Tables 3-1 and 3-2.
** ND = Not determined.

Diesel Allison (DDA) 4-53T and 4-71TI, the Westerbeke/Perkins Chrysler 4-108, and the Cummins NH-220.

The correspond' _ injection systems for these engines are as follows: The DDA/53 and DDA/71 both use a unit-type injector. One of the major differences is the style of tip used for each system. An N45 injector with a 6-hole tip is used in the DDA/53 engine; while an N65 injector with an 8-hole tip is used in the DDA/71 engine. A standard Cummins PT-type injector with an 8-hole tip is used in the NH-220 engine. A CAV-Lucas distributor pump with a pintle-type injector is utilized in the Westerbeke engine.

B. Test Fuels

The test fuels chosen and blended for this program were designed to cover a relatively broad range of viscosities and specific gravities. The selected base fuel was qualified to the current MIL-specification (MIL-F-16884H). This fuel was a Naval Distillate Fuel (NDF), obtained from the David Taylor Naval Ship Research and Development Center. In addition to the base fuel, a specification Heavy Marine Gas Oil (HMGO) and a standard DF-2 fuel were also selected as current fuels that might be used as emergency fuels. The remainder of the test matrix (eleven fuels and fuel blends) were blended to represent a range of fuel properties that might be encountered in future fuels.

The fuel blends representing future fuel properties were blended to provide fuels with viscosities at 40°C ranging from 5 to 19 cSt and specific gravities ranging from 0.86 to 0.89. Three levels of viscosities and three levels of specific gravities were chosen. Using a full factorial test design, this portion of the test matrix required nine fuel blends. An additional two fuels at the 5-cSt viscosity level were included in the test matrix in order to provide a broader range of specific gravities if needed.

The test fuels and their properties are listed in Table 2. Some fuels were obtained that met the desired fuel properties, while others were blended with the base fuel in order to obtain the desired properties. The fuels which required blending included test fuel Nos. 3, 6, 7, 9, and 12. The fuels were blended as follows:

Blend 3 - TL-415-1 contains 45 percent TL-415 + 55 percent NDF
Blend 6 - TL-415-2 contains 94 percent TL-415 + 6 percent NDF
Blend 7 - TL-619-1 contains 82 percent TL-619 + 18 percent NDF
Blend 8 - TL-619-2 contains 99 percent TL-619 + 1 percent NDF
Blend 12 - TL-619-3 contains 39 percent TL-619 + 61 percent NDF

III. TEST EQUIPMENT

A device designed and assembled at Southwest Research Institute (SwRI) was used to examine the diesel injection event in an environment thermodynamically similar to that encountered in an engine. The system (Figure 1) consisted of an injection and atomization bomb, an injection system drive and control system, and two spray diagnostic systems. These spray diagnostic systems were high-speed movie system and a laser droplet sizing system.

TABLE 2. FUEL INJECTION TEST FUEL MATRIX

Test Fuel No.	Fuel ID	ASTM D 445 Kinematic Viscosity at 40°C, cSt	ASTM D 1298 Specific Gravity at 15.6°C
0	Base Fuel (NDF)	2.75	0.849
1	DF-2	3.02	0.846
2	HMGO	6.2	0.874
3	TL-415-1[a]	5.0	0.861
4	TL-309[b]	4.9	0.874
5	TL-126	5.0	0.891
6	TL-619-1	12.8	0.857
7	TL-415-2	12.5	0.869
8	TL-323	12.3	0.893
9	TL-619-2	19.5	0.859
10	TL-671	19.5	0.870
11	TL-521	19.3	0.890
12	TL-619-3	5.2	0.852
13	TL-705	4.8	0.825

[a] 415-1 indicates a blend of Telura oils and F-76 base fuel.
[b] 309 indicates the unadulterated Telura oil.

A. Injection and Atomization Bomb

The purpose of the bomb was to allow observation of the characteristics of diesel-type fuel injection sprays in an environment which was at a density similar to that encountered in an engine. An inert atmosphere of nitrogen was used to prevent autoignition of the test fuel. The bomb had a cylindrical geometry with quartz-glass end plates which allowed direct visual observation and optical measurement through the bomb. Adaptors were made so that the various injection nozzles could be installed in the bomb.

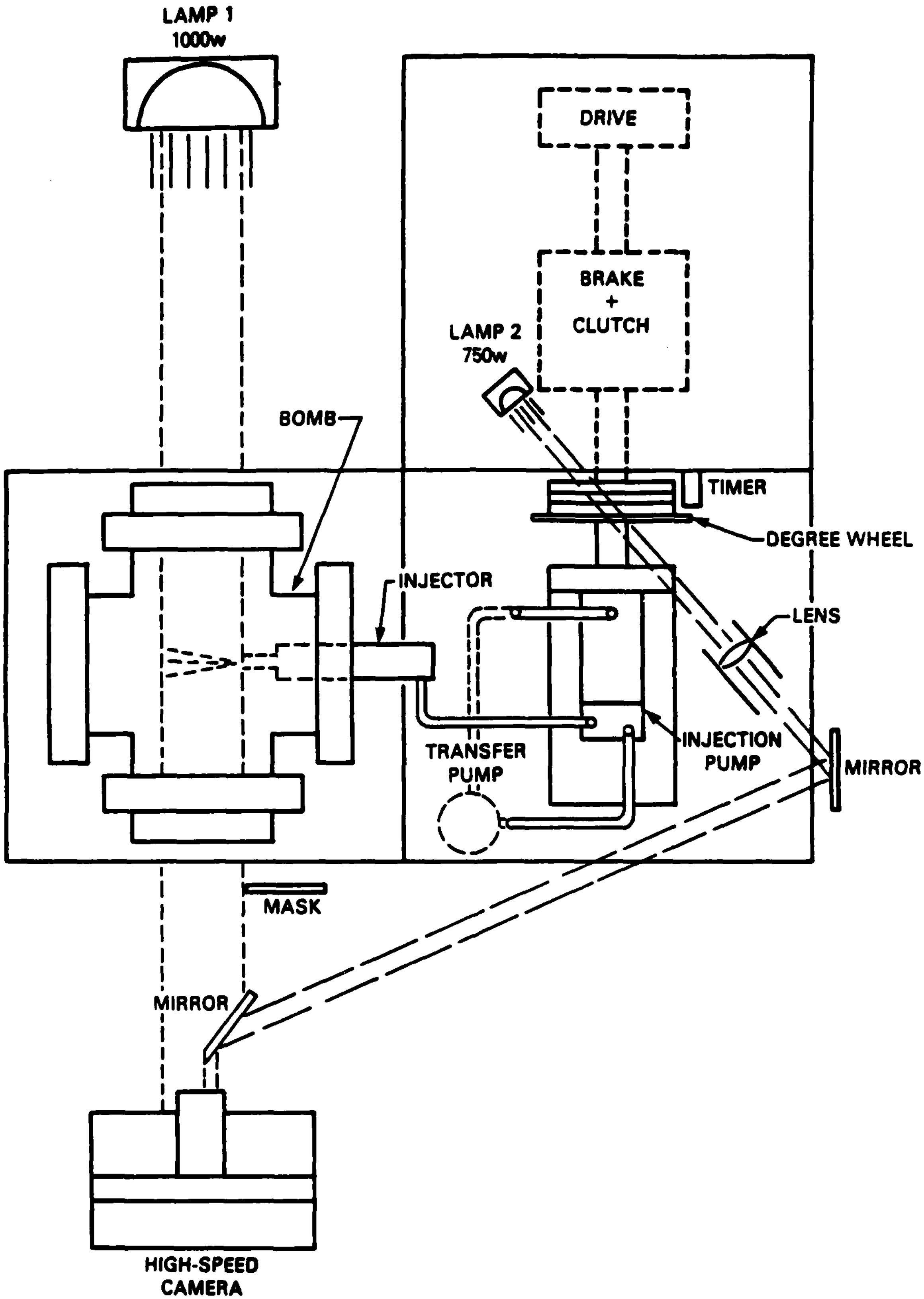

FIGURE 1. INJECTION TEST SYSTEM

B. Injection System Drive and Control System

The various injection systems were driven using a variable-speed electric motor coupled to the injection system through an electrical clutch. Control systems were built which allowed for timing and control of the various measurements relative to the start of injection. The control system engaged the clutch based upon an external signal from the high-speed camera and also was able to count the number of cam revolutions and engage a brake after a specific number of revolutions or injections. The control system was adjustable to obtain from 1 to 10 injection events.

C. High-Speed Movie System

The high-speed movies were taken using a Hycam II, 16-mm high-speed motion picture camera. The camera is capable of running 11,000 full frames per second or, with the installation of a quarter framing control head, at 44,000 quarter frames per second. The camera, equipped with a Sigma Zoom lens (35 to 75 mm focal length, f 2.8-2.4) and a 2X tele-extender, was positioned so that the lens was focused on the center of the spray. Back lighting was provided through the opposite window of the bomb using a 1000W tungsten-halogen lamp. For this program, 137-meter rolls of Kodak type 2498 RAR reversal, 16-mm film were used. The movie film speed was set at 25,000 quarter frames per second, or 40 microseconds between frames. The camera was equipped with an internal switch which closed when the camera was up to speed, thus activating the injection pump drive. The movies of the spray were analyzed using a Vanguard motion analyzer, which allowed reduction of the penetration rate and cone angle data. These data were then entered into a computer-based data management system for manipulation and storage.

D. Laser Droplet Sizing System

Droplet size data were obtained using a Malvern particle sizer modified to simultaneously measure the intensity of the forward-scattered laser light at several scattering angles. Simultaneous sampling made it possible to measure the drop size distribution in transient diesel sprays at any given instant. This computer-operated system gathered and reduced the light signal intensity data and provided various options for presentation of the size distribution data, including normal, log-normal, Rosin Rammler, and model independent distribution functions.

IV. EXPERIMENTAL PROCEDURE

The procedure for obtaining high-speed movies of the injection process was essentially the same for all injector-fuel combinations. The first step in testing each injection system was to install the injector in the injection and atomization bomb. Proper orientation of the injector in the bomb was necessary to prevent impingement of the spray on the quartz windows and to prevent obscuration of the individual jets. Multihole nozzles were orientated so that a clear view was obtained of at least one spray. Once installed in the bomb, the injector was not removed until testing was completed. This prevented any errors caused by orientating the injector from affecting the results.

Since each injection system was of a different design, instrumentation of each system was slightly different. However, in general there were several common variables which were controlled for each system. These variables were fuel temperature, pump or cam speed, fuel flow, and fuel pressure. Each of these variables would be expected to affect the spray characteristics. For example, changes in fuel temperature would alter the fuel viscosity and, therefore, affect the injection process. Since the main objective was to determine the effects of fuel properties on diesel spray characteristics, an attempt was made to hold the above variables constant for a given injection system. The value of these variables for each injection system are listed in Table 3.

Slight variations in fuel flow did occur from one fuel to another due to changes in fuel properties, mainly viscosity. It should be pointed out that it was not possible to measure the fuel flow during the acquisition of the high-speed movie. Fuel flow measurements were made before and after the movie and averaged together to obtain an estimate of the fuel flow during the movie.

Briefly, the procedure for actually taking the movies was as follows. A solvent and then the next test fuel were flushed through the injection and fuel system prior to

TABLE 3. INJECTION SYSTEM VARIABLES

	DDA/53	DDA/71	Pintle	Cummins
Fuel Flow (mL/1000 strokes)	61.7 ± 1.2	101.7 ± 2.8	23.9 ± .5	83.1 ± 2.0
Pump or Cam Speed (rpm)	1800	2000	1200	1067
Rack	Full	Full	Varied	N/A*
Fuel Temperature (°C)	36	29	37	24
Fuel Inlet Pressure (psi)	80	80	50	50**
Fuel Outlet Pressure (psi)	70	60	N/A	N/A

* N/A = Not Applicable.

** Fuel flow for Cummins injector is controlled via fuel pressure differential across a metering orifice. This differential pressure was maintained at approximately 50 pounds/sq. in. differential (psid).

switching to a new fuel. This procedure prevented contamination from previous test fuels. The operating variables were then checked and adjusted if necessary.

After the operating variables were set, a high-speed movie of the injection process was taken. Typically, film speed was approximately 25,000 quarter frames/sec. Using 137-meter rolls of film, approximately six injection events were recorded per film. Penetration and cone angle data were taken mainly from the second and third injections. Reasoning for this was that the first injection may not always be a good injection due to start-up effects and the later injections may be affected by changes in the bomb conditions due to the previous injections.

V. EXPERIMENTAL TEST MATRIX

The fuels matrix consisted of 14 fuels chosen to provide a wide range of viscosities and specific gravity. Nine of the fuels were selected to be tested during the high-speed movie phase of this program. These fuels were the base fuel (NDF), DF-2, HMGO, and Blends 5, 6, 8, 9, 11, and 13. These fuels represent the extreme points of the fuels matrix with respect to viscosity and specific gravity. Each of the 9 selected fuels were run in each of the four injection systems using the procedure previously described. High-speed movies were obtained of the injection process for each fuel/injection system combination.

The bomb conditions for the injection event were 26°C and 1.57 mPa. The bomb conditions were chosen to provide an environment density which was similar to that which would be found in an operating diesel engine. Ryan and Dodge (13) have shown that air density is one of the most important environmental parameter when examining penetration and cone angle data.

The main objective of this study was to determine the effect of viscosity and specific gravity on diesel spray characteristics. Testing at elevated temperature was not performed, since this would lead to high evaporation rates which would be dependent on the boiling point distribution of the fuel. In general, the boiling point distribution of a fuel can be correlated with other fuel properties, particularly viscosity. A fuel with a high viscosity will typically have a high boiling point distribution. Thus at elevated temperatures, it would be difficult to distinguish between changes in spray characteristics due to evaporation and changes in the boiling point distribution or due to changes in viscosity.

The drop-size measurements were made using the pintle nozzle. The use of this nozzle had several advantages. Since the direction of its spray is along its own axis, this nozzle was easy to orientate for the drop-size measurements. This particular nozzle also has a hollow-cone spray which is less dense than the jets which are observed for the other three injectors. Thus obscuration was less of a problem with the pintle nozzle. An abbreviated fuels matrix was selected and designed to indicate viscosity effects while minimizing the variation and, hence, the effect of specific gravity. The selected test fuels were the base fuel (NDF), HMGO, and Blends 7 and 10. Because of the possibility of spray impingement on the windows affecting the drop-size measurements, these tests were not made while the injector was mounted in the bomb. A simple holder was used to support the injector while the measurements were made. The conditions for these measurements were 26°C and atmospheric pressure.

VI. DATA ANALYSIS

High-speed movies were obtained of the injection process for the four different injection systems operating on nine test fuels. Each movie was examined, and tip penetration and cone angle data were measured using a Vanguard Motion Analyzer for each frame of the injection. By knowing the film speed, the penetration and cone angle data could be related to time. The penetration distances obtained from the motion analyzer had arbitrary units referred to as motion analyzer units (MAU). A scale was placed in the injection bomb next to the injector tip so that it could be seen in the films, thus the factor for converting MAU's to millimeters could be determined directly. Penetration distances and cone angle data were corrected for viewing angle if the direction of the spray was not parallel to the plane of the camera. This was necessary since penetration rates would appear to be lower if the spray was directed toward the camera.

The penetration and cone angle data, having been tabulated as functions of time, were then entered into the computer for each fuel/injection system combination. These data were then analyzed for each injection system. The analyses of the four injection systems are discussed separately in the following sections. Penetration versus time data is tabulated in the appendices for the Westerbeke, the DDA/53, and the DDA/71 injection systems. The Cummins penetration data are summarized in the section describing the Cummins data.

A. Westerbeke 4-108 Injection System

Analysis of the penetration data for the Westerbeke injection system (pintle nozzle) was relatively straight forward. For the pintle nozzle, the penetration distance was directly proportional to time as illustrated in Figure 2. This figure shows the tip penetration for the NDF fuel as a function of time. As illustrated, the penetration rate was constant and is given by the slope of the line. All fuels exhibited the same trend of constant penetration rate. Fuel-to-fuel comparisons were, therefore, easily made by comparing penetration rates for each fuel. Table 4 is a listing of the penetration rate for each fuel along with its viscosity at the test temperature and its specific gravity. Also included in Table 4 are the fuel flow rates for each fuel during the movies.

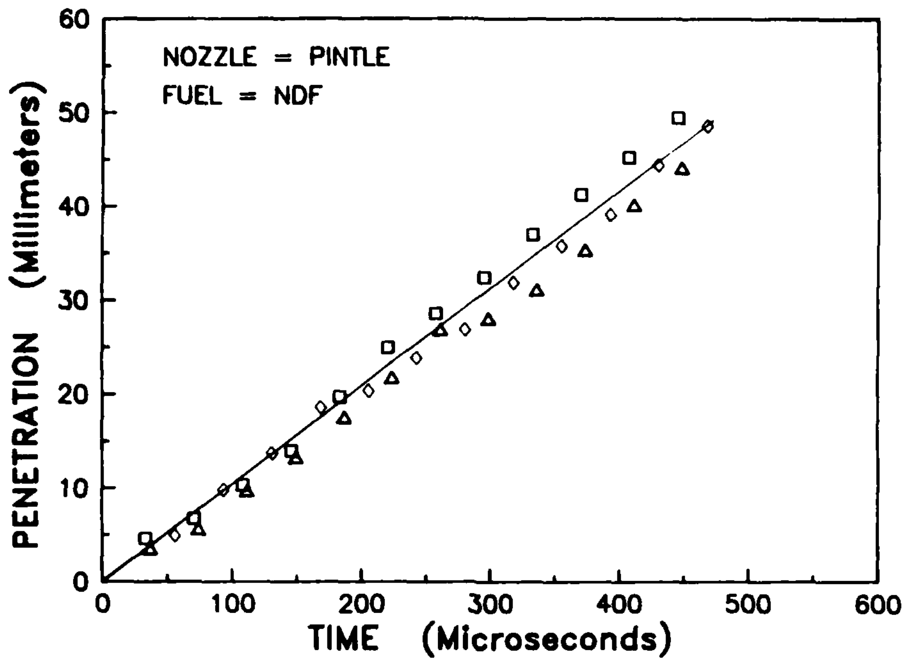

FIGURE 2. SPRAY TIP PENETRATION VERSUS TIME FOR BASE FUEL - PINTLE NOZZLE

TABLE 4. PENETRATION RATE DATA FOR PINTLE NOZZLE FOR EACH TEST FUEL

Fuel	Viscosity (cSt)	Specific Gravity	Fuel Flow Rate (mL/1000 stroke)	Penetration Rate (mm/msec)
NDF	3.45	0.849	23.6	102.41
DF-2	3.78	0.846	24.6	101.85
HMGO	8.60	0.874	24.4	101.65
Blend 5	6.59	0.891	28.6	101.59
Blend 6	20.60	0.857	23.1	90.14
Blend 8	19.63	0.893	23.1	89.73
Blend 9	35.02	0.859	24.7	93.27
Blend 11	29.86	0.890	23.6	91.95
Blend 13	6.35	0.825	23.9	103.09

The penetration rates in Table 4 are plotted versus the fuel viscosity in Figure 3. As shown in Figure 3, as viscosity increased, the penetration rate tended to decrease. There appears to be some scatter in the data, as plotted in Figure 3. However, it should be realized that certain fuels had different specific gravities and fuel flow was not quite constant for all fuels.

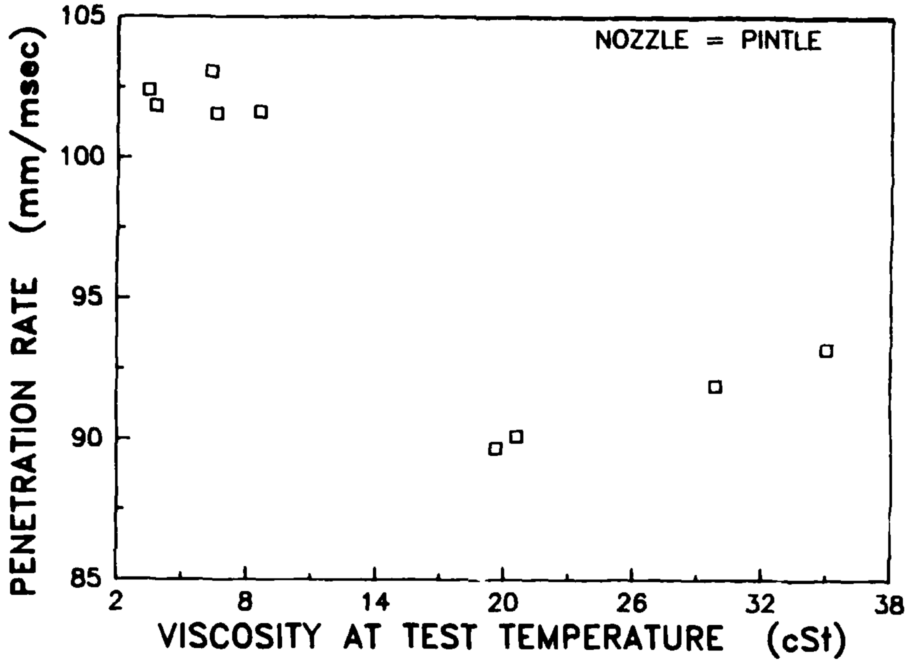

FIGURE 3. PENETRATION RATE VERSUS VISCOSITY FOR PINTLE NOZZLE

To separate the effects of specific gravity and fuel flow, a multiple linear regression was performed. The model is shown in Equation 4:

$$dP/dt = b_o + b_1(\text{vis}) + b_2(\text{spgr}) + b_3(\text{FFLW}) \tag{4}$$

where: dP/dt = penetration rate (mm/msec)
vis = viscosity (cSt)
spgr = specific gravity
FFLW = Fuel Flow Rate (mL/1000 strokes)

The results of the regression analysis are shown in Table 5. Among the results are the estimated coefficients of the regression equation, the standard error of the

TABLE 5. REGRESSION ANALYSIS OF PENETRATION RATE VERSUS VISCOSITY, FUEL FLOW RATE AND SPECIFIC GRAVITY FOR PINTLE NOZZLE
(R^2 = 0.8780, STD ERR = 0.2571)

Variable	Coefficient	Standard Error	t-Statistic	p-Value
Intercept	1.124652	6.336315	0.177	0.8661
Viscosity	-0.039983	0.008281	-4.828	0.0048
Fuel Flow Rate	0.405605	0.162712	2.493	0.0550
Specific Gravity	-0.545382	4.406204	-0.124	0.9063

coefficients, and a t-statistic for each coefficient (the ratio of coefficient to its standard error). A large absolute value of the t-statistic for a coefficient indicates that the particular term is important and helpful in predicting the dependent variable, dP/dt. A small t-statistic indicates that the particular term does not contribute to predicting the penetration rate and its coefficient has an increased probability of being zero. The decision on whether the t-statistic is large or not is typically based upon its associated p-value, which is also contained in Table 5. Generally, a t-statistic with a p-value greater than 0.05 is considered small and indicates that particular variable can be eliminated from the regression equation with little or no effect.

As indicated in Table 5, both the intercept and specific gravity have p-values greater than 0.05, meaning these terms have little value in predicting the penetration rate. These terms were removed from the regression equation resulting in the final equation in the form of Equation 5.

$$dP/dt = b_1\,(\text{vis}) + b_2\,(\text{FFLW}) \tag{5}$$

The estimated coefficients for this regression equation are shown in Table 6. The negative coefficient for viscosity indicates that as viscosity increases, the penetra-

TABLE 6. REGRESSION ANALYSIS OF PENETRATION RATE VERSUS VISCOSITY AND FUEL FLOW RATE WITH NO INTERCEPT FOR PINTLE NOZZLE
(R^2 = 0.999, STD ERR = 0.218)

Variable	Coefficient	Standard Error	t-Statistic	p-Value
Viscosity	-0.040300	0.006505	-6.195	0.0004
Fuel Flow Rate	0.433180	0.005071	85.417	0.0001

tion rate decreases. The effect of viscosity on the penetration rate at constant fuel flow is illustrated in Figure 4. This is in agreement with previous work.(13) The positive coefficient for fuel flow indicates that higher fuel flow rates have higher penetrations. It should be noted that even though the variation in fuel flow

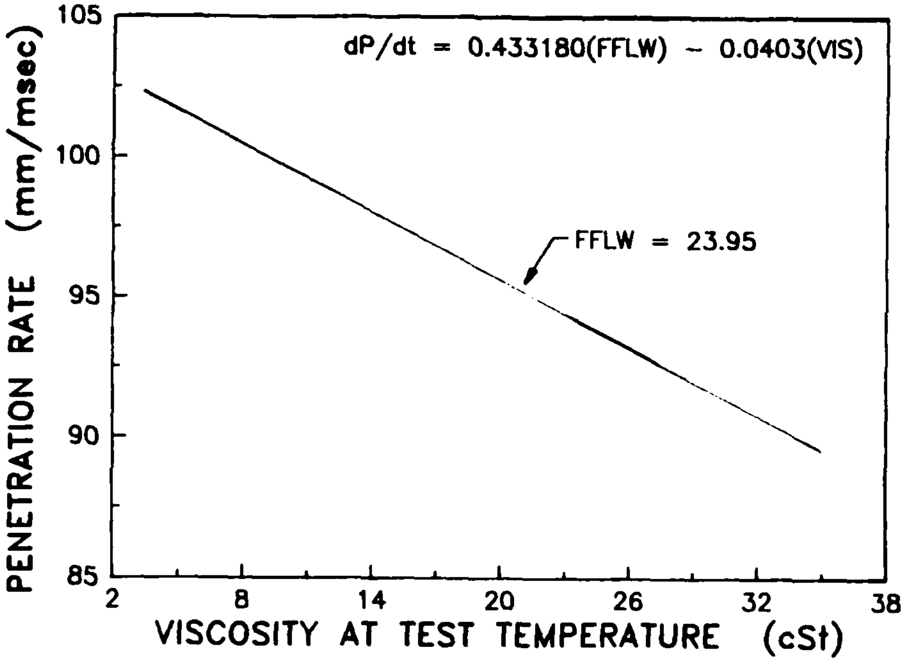

FIGURE 4. EFFECT OF VISCOSITY ON PENETRATION RATE AT CONSTANT FUEL FLOW RATE FOR PINTLE NOZZLE

was small (less than 3 percent), it had a significant effect on the penetration rate. This variable is often incorrectly ignored when analyzing this type of data.

Cone angle data for the pintle nozzle was not quite as straight forward to analyze as the penetration data. Obtaining the penetration data from the high-speed movies requires that only one judgment be made: the location of the tip of the spray. That is simply a matter of determining which point represents the tip of the spray. When estimating the cone angle, more difficult decisions must be made in defining the lines that represent the lower and upper boundaries of the spray. Obviously, measurements of both the penetration and cone angle require some judgment. In general, the more difficult the decision, the more variation there is in the measured value.

One method for eliminating measurement variability is to average the measurements to obtain a single value. For the pintle nozzle, the cone angle data for frames 10 through 14 were averaged for each injection. This single value for the cone angle represents the average cone angle from approximately 400 to 500 microseconds after the beginning of injection. In general, the cone angle during this period was fairly constant, and slight variations were mostly random in nature and not dependent on time. The average cone angle was determined for the second, third, and fourth injections. These three values were then averaged to obtain a single cone angle estimate for each movie. These data are tabulated in Table 7 and plotted versus fuel viscosity in Figure 5. As illustrated in the figure, the broad variation in viscosity had little effect on the cone angle.

Drop-Size Measurements on Pintle Nozzle: Generally, increases in fuel viscosity lead to increases in drop sizes in sprays. Since evaporation times are proportional to the drop diameter squared, increased viscosity could result in increased evaporation times. Increased evaporation times could lead to poorer starting, reduced efficiency, and increased soot formation in diesel engines, depending upon the engine design. The effects of viscosity on atomization have been widely documented in many gas turbine and oil burner nozzles, but very little information exists for diesel sprays. The fact that diesel sprays are both intermittent and extremely dense, at least in multihole injection nozzles, combine to make spray drop size measurements very difficult. In fact, for sprays into

TABLE 7. AVERAGE CONE ANGLE DATA FOR PINTLE NOZZLE

Film	Fuel	Average Cone Angle
030601	DF-2	6.5
030801	NDF	6.1
030802	HMGO	5.8
030805	HMGO	5.5
031101	Blend 5	6.2
031102	Blend 6	7.3
031103	Blend 8	5.5
031201	Blend 9	5.6
031202	Blend 11	5.6
031203	Blend 13	5.3
040401	Blend 13	4.7
040402	DF-2	5.2

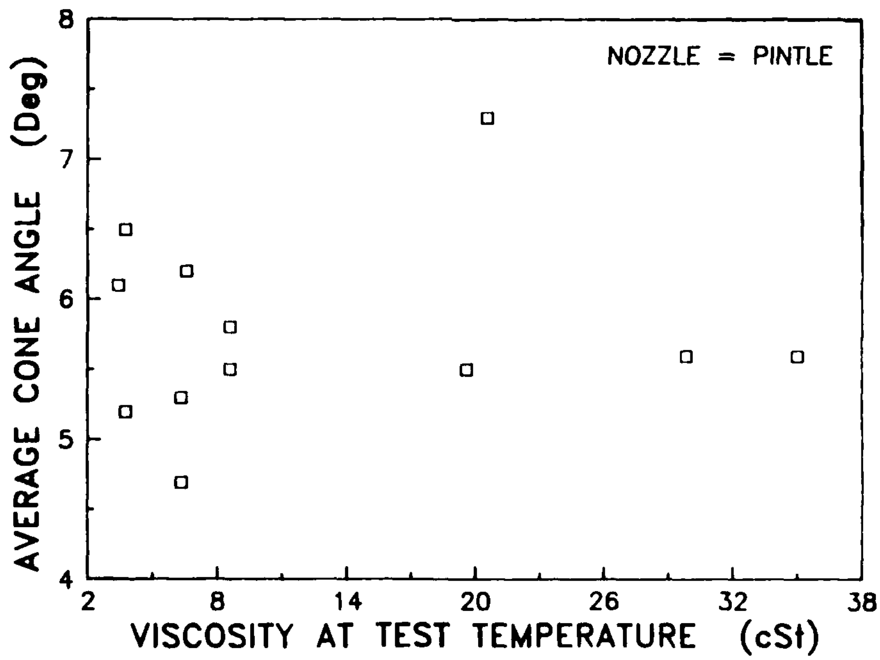

FIGURE 5. AVERAGE CONE ANGLE VERSUS FUEL VISCOSITY FOR PINTLE NOZZLE

atmospheric pressure air, high-resolution photography performed at SwRI indicates very poor and incomplete atomization with many large ligaments throughout the core for multihole nozzles even on standard diesel fuel.(13) At the edge of the spray, the ligaments break into drops typically ranging from 5 to 30 micrometers in diameter. For injection into higher pressure air, the fuel jet is mostly optically opaque due to the increased fuel drop density, but some ligaments are still observed at the very edge of the spray.

The pintle nozzle was selected for the drop-size measurements because it had a geometrically simple spray pattern (one spray on axis) and a relatively transparent spray. To make measurements in the intermittent spray, the Malvern automated laser-diffraction drop sizing instrument was modified to simultaneously freeze and hold the diffraction signatures on all 30 detectors at any instant in time, adjustable from zero to 10 milliseconds after the needle lift signal. These signals are acquired over a period of 10 microseconds and held until the multiplexer reads the signal level and reports the value to the computer. This variable time-delay system allows temporal variations in spray quality to be accurately monitored. For these tests, a delay of about 0.7 msec was necessary before any of the spray reached the measurement location at 51 mm from the nozzle tip. An additional 0.3 msec delay was required to allow the transient interface at the tip of the spray to pass by the sample location.

Data were recorded at 51 mm (2 in.) from the nozzle tip through the centerline of the spray, and at a time of 1 msec after needle lift. Significant fuel effects on atomization were observed as shown in Figure 6, with increased viscosity resulting in larger drop sizes. Two averages are shown in Figure 6, the volume median diameter and the Sauter mean diameter. The volume median is that diameter for which one-half of the spray volume is contained in drops whose diameters are smaller than the median value and the other half of the spray volume is in drops larger than the median. The Sauter mean diameter represents the diameter of a fictitious uniform (monodisperse) spray having the same total droplet surface area and volume as the actual spray. The droplet surface area and volume determine the evaporation rate, which is the reason that Sauter mean diameter (SMD) is commonly used to characterize average drop sizes in fuel sprays. The large difference between the volume median diameter and the SMD indicates that the

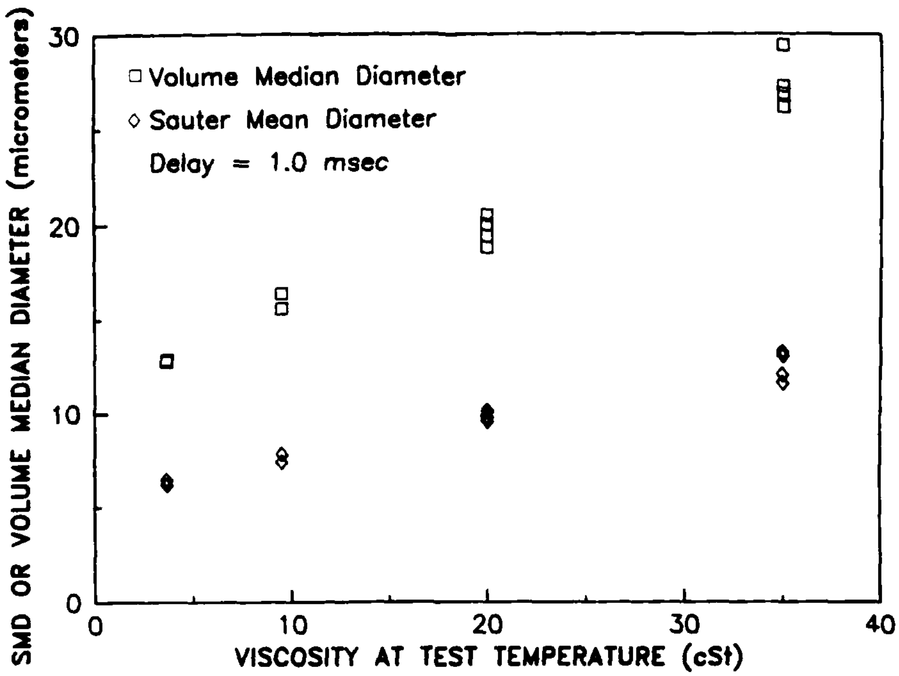

FIGURE 6. EFFECT OF VISCOSITY ON ATOMIZATION FOR PINTLE NOZZLE

drop-size distribution of the spray was fairly broad. Typically, the viscosity effect on SMD for pressure swirl atomizers (gas turbine or oil burner nozzles) is correlated in a form SMD $\sim (\text{vis})^{a}$, with the value of a being approximately 0.25. If the same form is used to correlate these data, the value of a is 0.30 and the correlation coefficient in log-log space is 0.985, with 1.0 being a perfect correlation. Thus, the relative effect of viscosity variations on atomization in the pintle injectors can be estimated from this relation.

B. Cummins NH-220 Injection System

Fuel sprays from a Cummins PT Injector are inherently different from those of injectors with plunger/needle assemblies, (e.g., DDA/53), in that they have no easily recognizable start of injection. The commonly used plunger/needle assemblies employ a plunger moving downward to compress fuel, and a spring-loaded needle to open when fuel pressure is high enough to overcome the force of the spring. The start of injection is easily defined at this point, and injection proceeds continuously until fuel pressure drops again and allows the spring to close the needle.

Cummins PT injectors do not have spring-loaded needles to seal off the fuel from the orifices in the tip. In the Cummins injector, this sealing function is performed by the conical tip of the plunger which seats in the tip. When the plunger is raised, fuel is allowed to flow for a specified length of time into the barrel or cup region. This metering period occurs during the latter half of the intake stroke and most of the compression stroke. When the plunger begins moving down, it seals off the fuel inlet port and forces the fuel out of the cup region through the spray tip. The amount of fuel injected is determined by the pressure of inlet fuel and the time allowed for inlet fuel metering. During the metering process, fuel is flowing into the cup region which communicates directly with the combustion chamber via the nozzle orifices. A significant amount of air can enter the cup region during metering causing an inhomogeneous compressible mixture to be formed which, when forced out the spray tip, results in spurts and pulses of fuel rather than a continuous spray. Observations of the high-speed movies show that often the spray pulses several times making it difficult to determine when injection begins and what its characteristics are until it moves a significant distance from the nozzle tip. This particular problem was more prevalent in the bomb than it would be in an engine, since the bomb was maintained at the elevated test pressure during the metering process.

The high-speed movies confirmed that these pulses occurred in each injection event, usually as a sequence of several short bursts followed by one long, steady pulse. Figure 7 presents data from a typical injection where the spray tip of this final pulse could be distinguished from the cloud caused by previous pulses. This example shows that fuel from the main injection pulse travels faster than fuel from the previous pulses, and eventually overtakes it approximately 30 mm from the nozzle tip. Beyond the 30-mm region, only one spray tip could be distinguished--made up mostly of fuel from the main injection pulse continuing at the same penetration rate. It was concluded from this that the latter part of the injection (after the spray has traveled about 30 mm) represents the main injection pulse unobscured by previous pulses. For this reason, all the spray penetration data presented here was taken when the spray tip was in the 30-60 mm range (using the average of second and third injections), and cone angle data was taken at corresponding locations (using the second injection). Penetration rates were calculated using a least square technique to determine the slope of penetra-

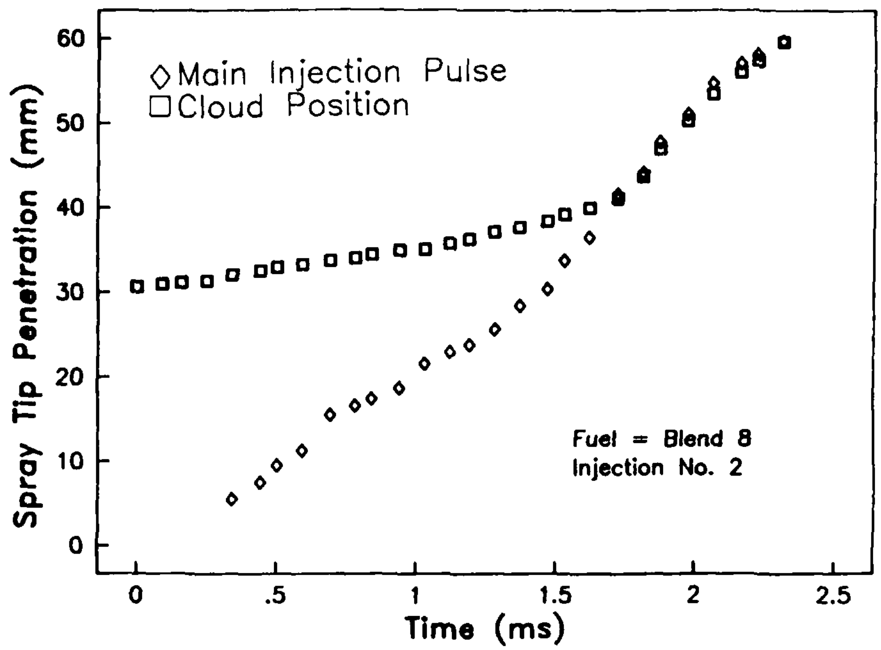

FIGURE 7. SPRAY TIP PENETRATION VERSUS TIME FOR BLEND 8 - CUMMINS INJECTOR

tion/time curves. *Cone angles in the 30-60 mm range were averaged to give a* single cone angle for each injection.

Results obtained for cone angle and penetration rate calculations are summarized in Table 8 along with the fuel properties, viscosity and specific gravity. Since

TABLE 8. PENETRATION RATE AND CONE ANGLE DATA FOR CUMMINS INJECTOR FOR EACH TEST FUEL

Fuel	Fuel Flow (mL/1000 strokes)	Viscosity (cSt)	Specific Gravity	Average Penetrate Rate (mm/msec)	Cone Angle Degrees Inj. No. 2
DF-2	83.0	4.40	0.846	20.08	11.4
NDF	80.3	4.10	0.849	16.44	11.3
HMGO	81.5	10.23	0.874	35.92	16.3
Blend 5	85.2	7.94	0.891	32.67	13.2
Blend 6	85.3	25.78	0.857	36.78	15.6
Blend 8	85.3	23.38	0.893	68.82	14.1
Blend 9	81.8	40.82	0.859	72.74	14.8
Blend 11	82.1	40.24	0.890	77.42	12.9
Blend 13	80.0	7.64	0.825	21.32	13.2

specific gravity and fuel flow changed only by a small percentage, it is difficult to determine whether they have a significant effect. Viscosity, however, varies over a much larger range, and a plot of penetration data versus viscosity, shown in Figure 8, indicates a definite trend. As shown in the figure, the penetration rate increases with increasing viscosity.

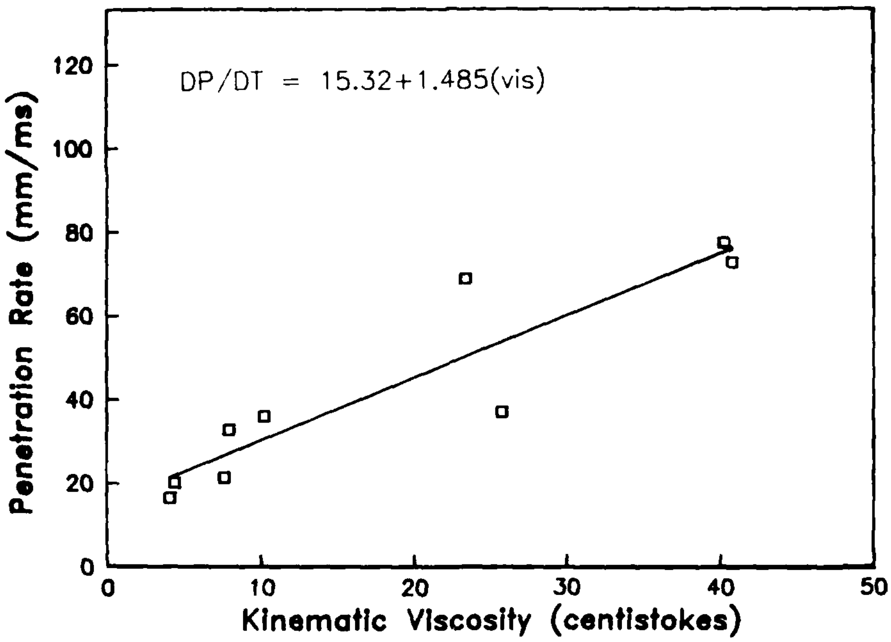

FIGURE 8. EFFECT OF VISCOSITY ON PENETRATION RATE FOR CUMMINS INJECTOR

Cone angle data, on the other hand, did not appear to correlate well with any of the fuel properties studied. The average cone angle data from Table 8 is plotted versus viscosity in Figure 9. As shown in Figure 9, the average cone angle appears to increase initially and then decreases at the higher viscosities.

C. <u>DDA/53 Injection System</u>

Unlike the pintle nozzle and the Cummins injector, the penetration data for the Detroit Diesel injectors were not directly proportional to time throughout the entire range of data. This is illustrated in Figure 10 in which the tip penetration of

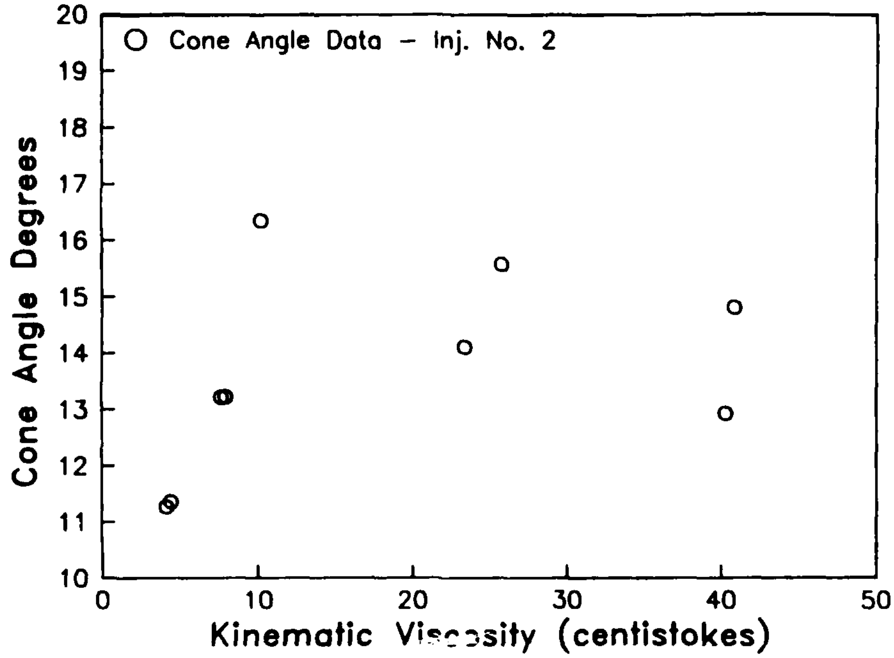

FIGURE 9. AVERAGE CONE ANGLE VERSUS FUEL VISCOSITY FOR CUMMINS INJECTOR

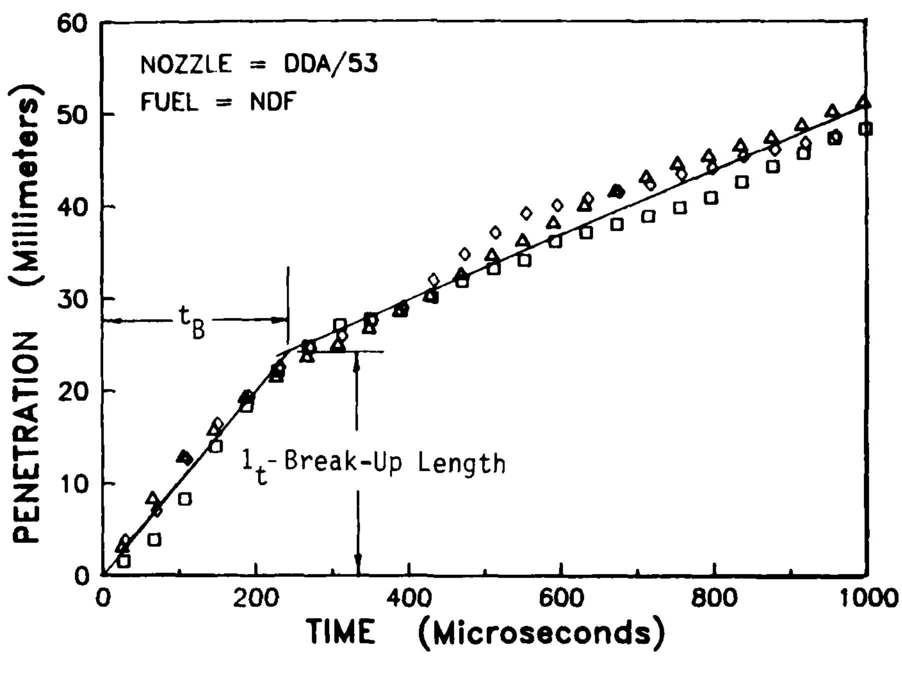

FIGURE 10. TIP PENETRATION VERSUS TIME FOR BASE FUEL - DDA/53 INJECTOR

the base fuel is plotted versus time. Although the penetration data initially appear to be linear with time, the tip penetration rate eventually decreases, thus introducing curvature. This actually is very common and has been reported by several researchers.(8,9,13) The explanation of this trend comes from the observation that initially the fuel spray is actually a solid core of liquid. After a certain distance, air entrainment results in the widening of the jet and ultimately leads to break-up of the liquid core into drops. These two regions can be differentiated in Figure 10 by the change in slope of the penetration data.

The point at which this change in slope occurs, the jet break-up length, can be estimated by locating the intersection of two straight lines fitted to the two regions of the penetration data. This method is illustrated in Figure 10 for the base fuel. The break-up length, the time that break-up occurs, and the penetration rates for both regions of the curves are listed in Table 9. Also listed in Table 9 is the fuel viscosity at the test temperature, the fuel flow rate, and an average cone angle for each fuel. The cone angle shown in the table was obtained by numerically averaging the cone angle of the spray between 400 and 550 microseconds.

The *initial penetration rates in* Table 9 are plotted versus fuel viscosity in Figure 11. As indicated in the figure, there was significant amount of scatter in the data for the lower viscosity fuels. Therefore, it did not appear that any variation in initial penetration rate could be attributed to variation in fuel viscosity. Multiple linear regression techniques were also unable to attribute the variation in initial penetration rate to any of the independent variables (viscosity, specific gravity, or variations in fuel flow rates).

The jet break-up length might be considered a better parameter for examining the effects of fuel properties on spray characteristics since the break-up length indicates how far from the nozzle atomization occurs. Ideally, the atomization should occur as close to the nozzle tip as possible, thus a short break-up length is desirable.

Figure 12 indicates the effect of viscosity on the break-up length. As illustrated, it appears that an increase in viscosity tends to increase the break-up length.

TABLE 9. SUMMARY OF SPRAY PARAMETERS FOR THE DDA/53 INJECTOR

Fuel	Viscosity (cSt)	Initial Penetration Rate (mm/msec)	Fuel Flow Rate (mL/1000 strokes)	Penetration Rate After Break-Up (mm/msec)	Cone Angle	l_B-Break-Up Length (mm)	t_B-Time to Break-Up (μsec)
DF-2	3.29	113.5	60.7	30.1	13.6	28.17	248.1
NDF	3.02	101.9	60.6	29.5	14.2	27.96	274.3
HMGO	6.94	88.9	61.0	30.4	15.7	28.02	315.1
Blend 5	5.55	117.4	62.3	33.4	14.3	27.91	237.7
Blend 6	14.49	94.3	62.5	31.8	12.0	27.44	290.8
Blend 8	14.25	88.5	60.4	28.4	12.4	31.46	355.3
Blend 9	23.05	107.9	63.0	26.3	12.6	30.74	284.8
Blend 11	22.76	101.1	63.0	29.5	14.1	29.11	287.5
Blend 13	5.36	105.6	60.3	30.1	13.9	29.60	280.2

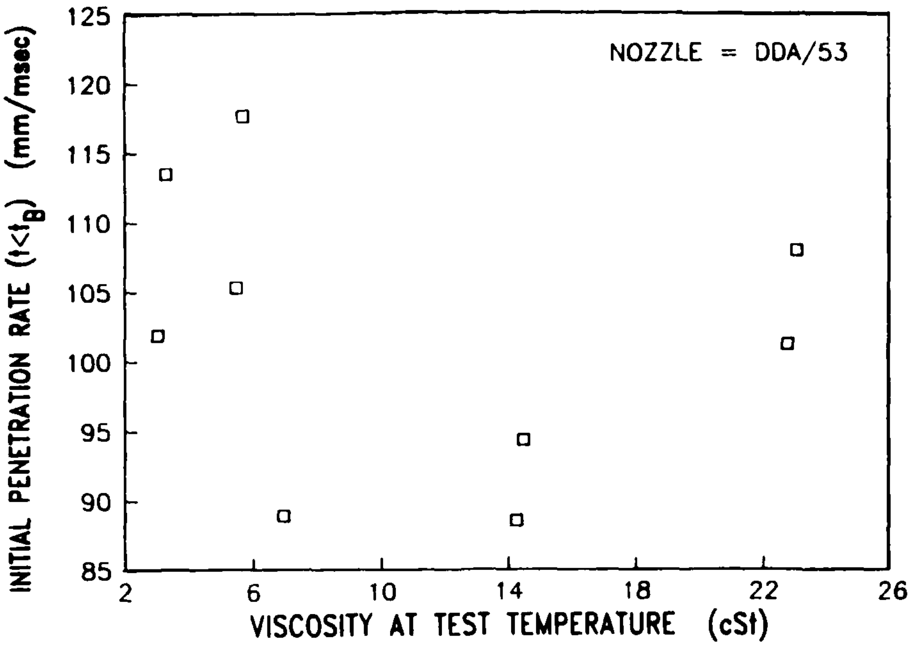

FIGURE 11. INITIAL PENETRATION RATE VERSUS VISCOSITY FOR DDA/53 INJECTOR

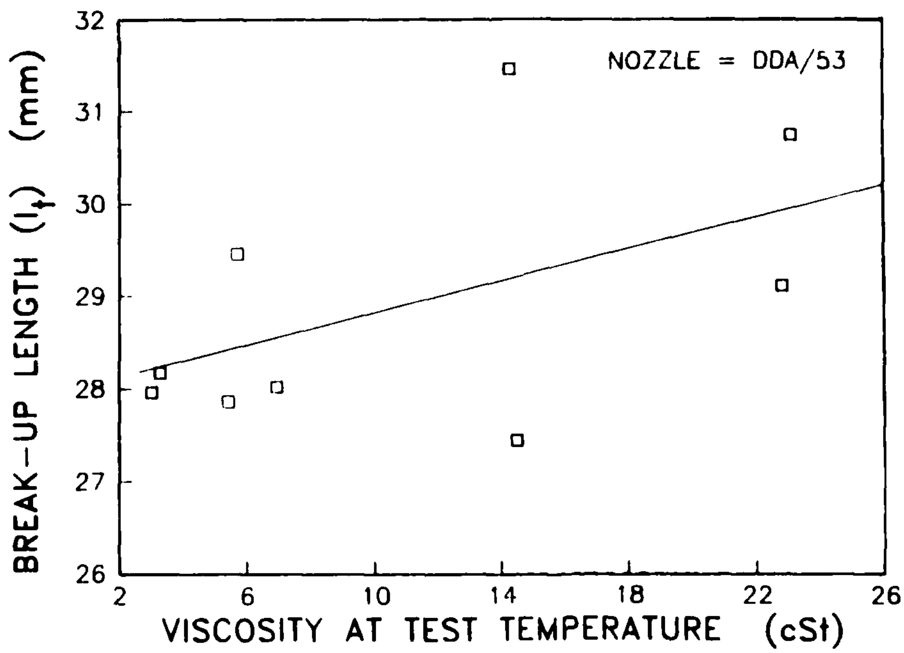

FIGURE 12. BREAK-UP LENGTH VERSUS VISCOSITY FOR DDA/53 INJECTOR

The average cone angle data for each fuel is plotted versus fuel viscosity in Figure 13. As shown in Figure 13, an increase in viscosity resulted in a decrease in the average cone angle.

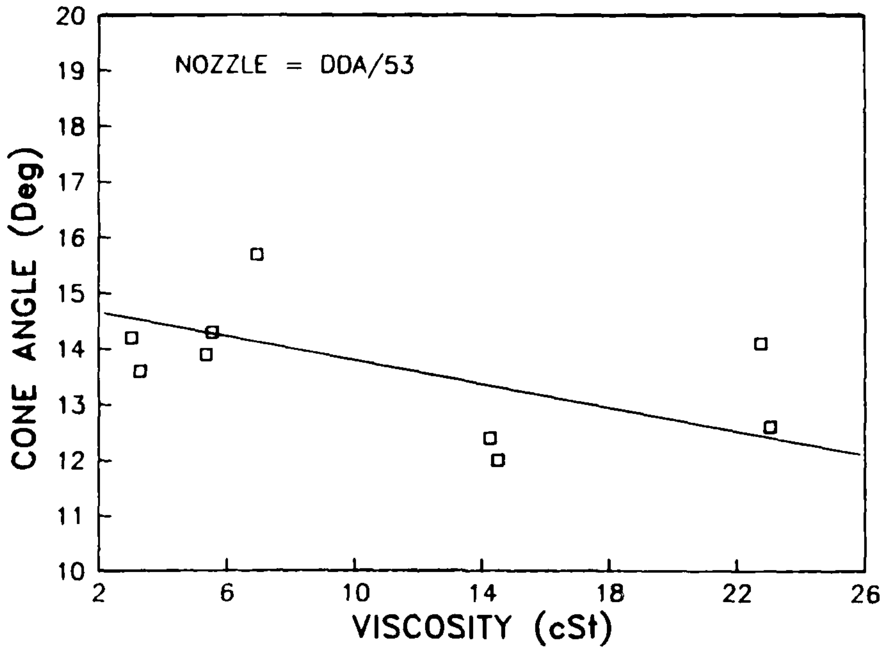

FIGURE 13. AVERAGE CONE ANGLE VERSUS VISCOSITY FOR DDA/53 INJECTOR

Typically, a decrease in cone angle results in an increase in the penetration rate. Since the cone angle data was averaged during the period of time between 400 and 550 microseconds, the appropriate penetration rate to examine would be the rate during this period which would be after break-up. The penetration rate after break-up is plotted versus fuel viscosity in Figure 14. As viscosity increased, the penetration rate decreased. This trend is opposite the expected effect and could be related to a viscosity-related change in the internal dynamics of the injection system or in the jet break-up process.

D. DDA/71 Injection System

The spray characteristics of the DDA/71 injector (N65) are very similar to the spray characteristics of the DDA/53 injector (N45). As illustrated in Figure 15, the

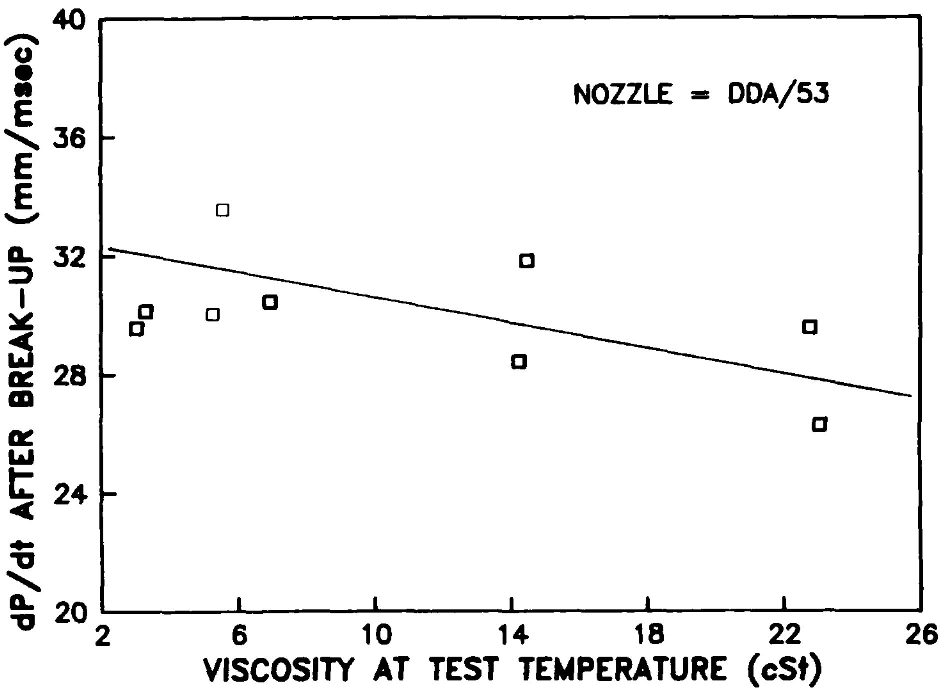

FIGURE 14. PENETRATION RATE AFTER BREAK-UP VERSUS VISCOSITY FOR DDA/53 INJECTOR

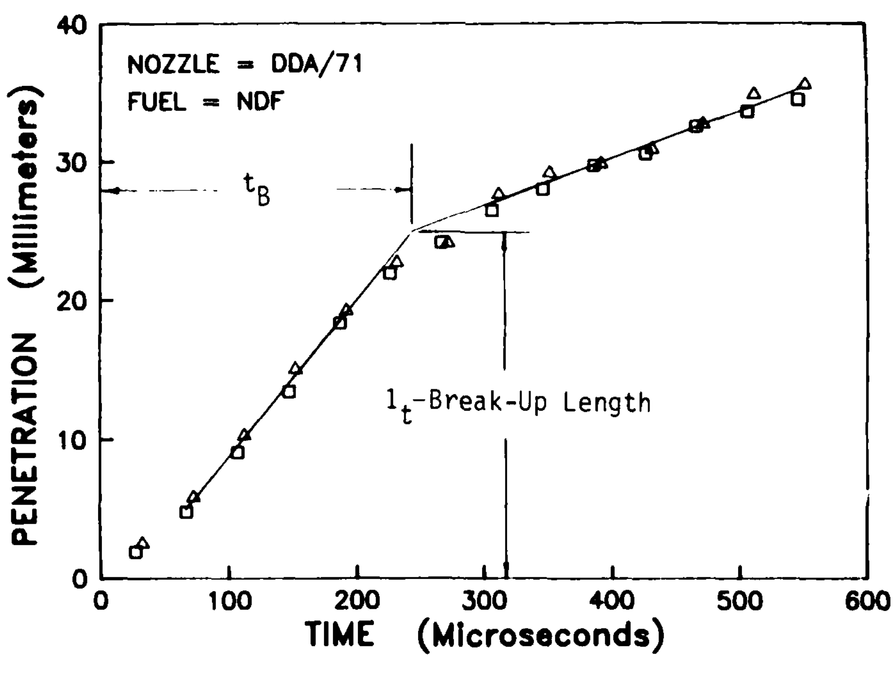

FIGURE 15. TIP PENETRATION VERSUS TIME FOR BASE FUEL - DDA/71 INJECTOR

tip penetration for the base fuel was, initially, linear with time. At approximately 25 mm, the liquid core breaks up and the tip penetration rate decreases. This effect was also evident for the DDA/53 injector. Therefore, analysis of the DDA/71 data is very similar to the analysis of the DDA/53 data. Table 10 summarizes the penetration rate and cone angle data for each fuel. Also included in the table are the viscosity, fuel flow rate, the break-up length, and the time at which the break-up occurs.

The initial penetration rate is plotted versus fuel viscosity in Figure 16. As with the DDA/53 injector, the initial penetration rate for the DDA/71 injector does not appear to be related to the viscosity of the fuel.

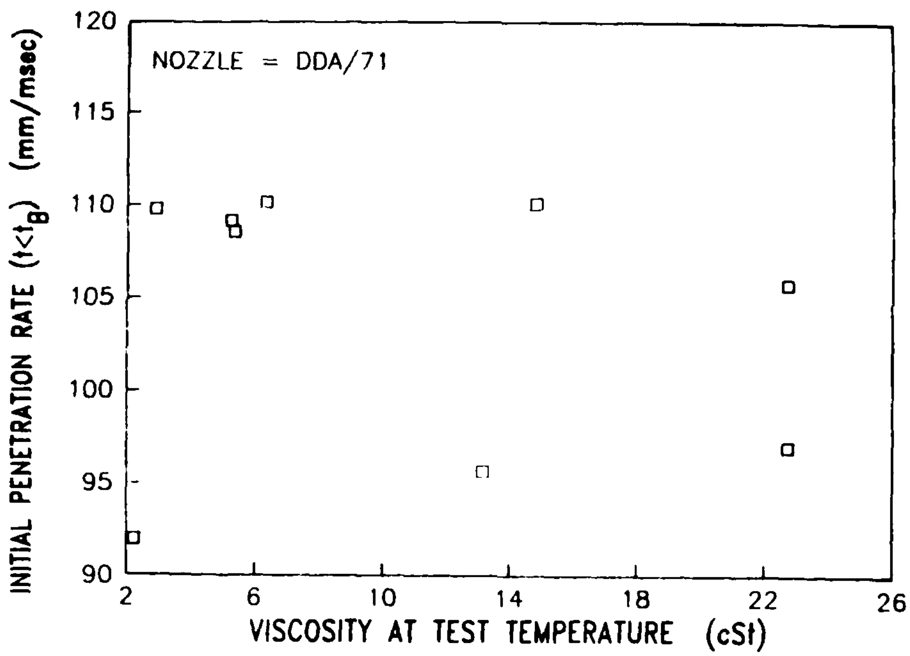

FIGURE 16. INITIAL PENETRATION RATE VERSUS VISCOSITY FOR DDA/71 INJECTOR

Figure 17 illustrates the effect of viscosity on the break-up length for the DDA/71 injector. An increase in fuel viscosity resulted in an increase in the break-up length. This trend is in agreement with that observed for the DDA/53 injector.

TABLE 10. SUMMARY OF SPRAY PARAMETERS FOR THE DDA/71 INJECTOR

Fuel	Viscosity (cSt)	Initial Penetration Rate (mm/msec)	Fuel Flow Rate (mL/1000 strokes)	Penetration Rate After Break-Up (mm/msec)	Cone Angle	l_B-Break-Up Length (mm)	t_B-Time to Break-Up (μsec)
DF-2	2.24	92.0	97.0	43.6	6.5	26.17	285.0
NDF	2.89	109.8	99.8	41.4	7.5	24.22	247.7
HMGO	6.35	110.2	105.1	43.0	6.0	28.23	280.8
Blend 5	5.26	109.2	106.1	40.5	6.2	28.22	267.5
Blend 6	14.89	110.0	103.2	50.6	4.8	25.40	229.9
Blend 8	13.23	96.6	101.5	53.7	5.1	30.40	325.0
Blend 9	22.73	105.8	101.7	55.6	5.2	29.88	298.6
Blend 11	22.76	97.0	104.3	*	5.0	*	*
Blend 13	5.36	108.6	98.9	45.4	6.2	25.60	263.5

* *Data could not be estimated.*

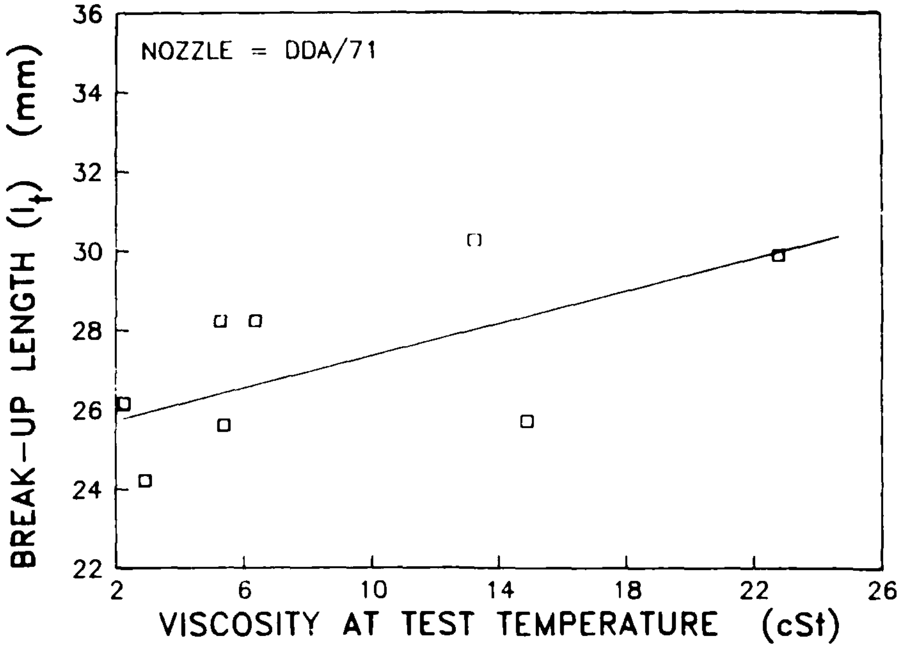

FIGURE 17. BREAK-UP LENGTH VERSUS VISCOSITY FOR DDA/71 INJECTOR

The effect of viscosity on the cone angle is illustrated in Figure 18, which is a plot of the average cone angle versus fuel viscosity. As indicated by the figure, as viscosity increased, the average cone angle decreased. The decrease in cone angle was accompanied by an increase in the penetration rate, as indicated in Figure 19. As viscosity increased, the penetration rate after break-up increased.

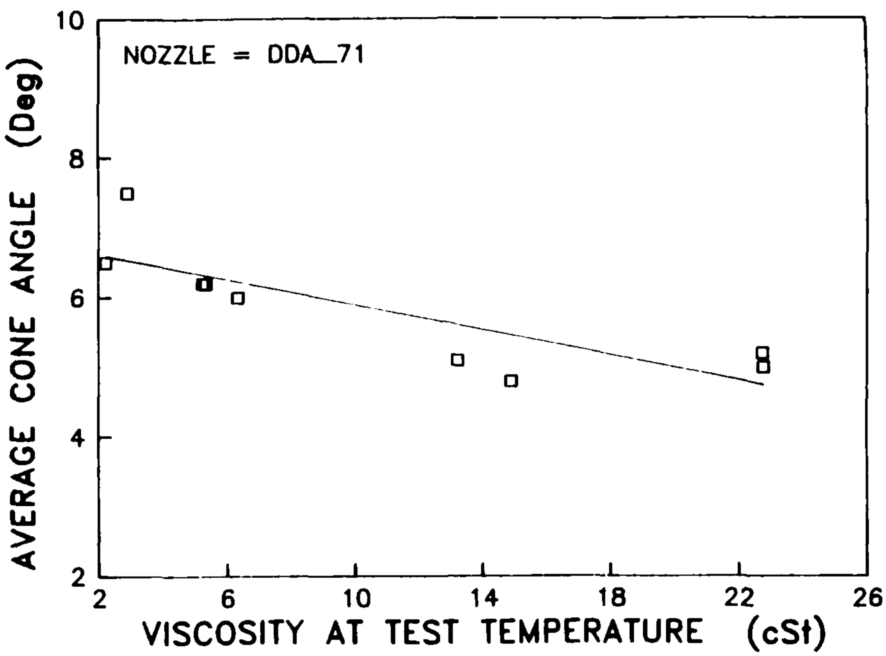

FIGURE 18. AVERAGE CONE ANGLE VERSUS VISCOSITY FOR DDA/71 INJECTOR

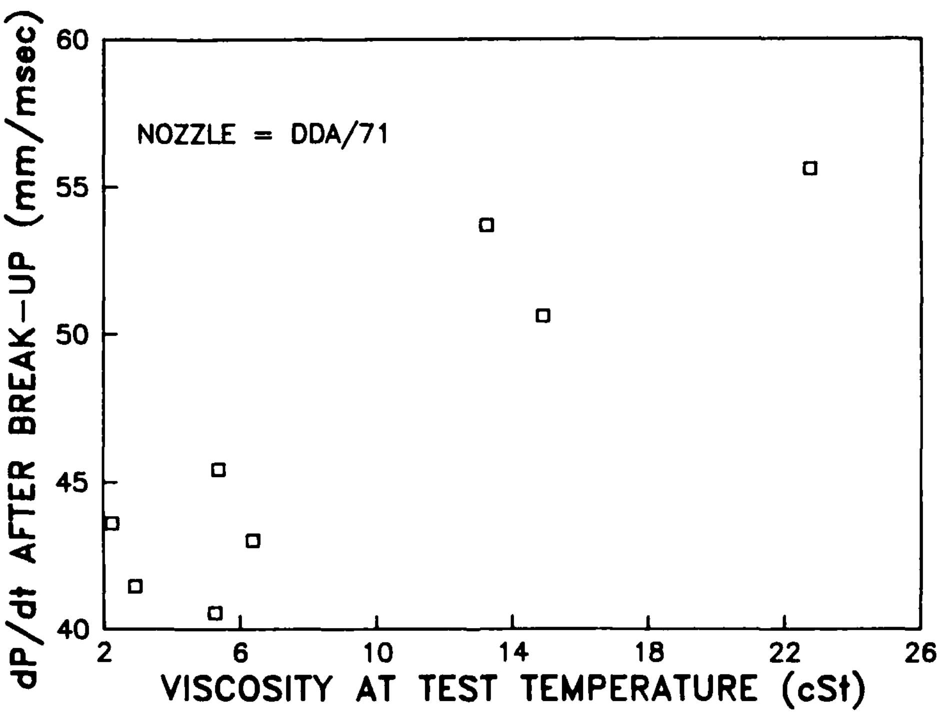

FIGURE 19. PENETRATION RATE AFTER BREAK-UP VERSUS VISCOSITY FOR DDA/71 INJECTOR

VII. DISCUSSION

A. Pintle Injector

Analysis of the pintle nozzle penetration data indicated that statistically significant changes in the penetration rate occurred due to changes in fuel viscosity. In the most extreme case, there was a 14-percent difference between the predicted penetration rate (Equation 5) of the base fuel, with a viscosity of 3.45 cSt and Blend 9 with a viscosity of 35.0 cSt. Physically this means that the tip of the spray for the NDF would take 0.488 msec to penetrate 50 mm into the combustion chamber, while Blend 9 would take 0.558 msec. The time difference would be 0.07 msec or approximately 0.5 crankangle degrees at 1200 RPM. This presentation is not entirely accurate due to elevated temperatures and turbulence in the combustion chamber that would affect the actual penetration. However, for the sake of argument accept these values and consider what effect these differences would have on engine performance.

As stated in the introduction, fuel impingement upon the piston or cylinder wall could lead to reduced efficiency and durability problems. Since the test fuels tended to penetrate at a slower rate than the base fuel, it would appear that impingement would not be a problem with the Westerbeke 4-108 engine. Impingement, however, would also be a function of drop-size distribution of the spray since this would control the evaporation rate along with fuel volatility. The drop-size measurements indicated that the more viscous fuels tended to have a spray with a larger drop-size distribution. In the engine, the larger drops would not evaporate as quickly and, even though they penetrate at a slower rate, they might survive long enough to impinge upon the piston or wall. With the current data, it is not possible to predict if any of the test fuels would present durability problems due to impingement. Information on the penetration rate or the drop-size distribution at elevated temperature is required.

Combustion of the fuels is another area which will be affected by the spray characteristics. As previously indicated, it takes the most viscous fuel 0.07 msec longer than the base fuel for its spray tip to reach 50 mm. This slight delay might be expected to effect the fuel-air mixing and thus the ignition delay. Elevated temperatures do have a slight effect on penetration rate.(13) As temperature increases, the tip penetration rate decreases as a result of disappearance of the tip due to evaporation. This, of course, gets back to the atomization characteristics (drop-size distribution) which affects the evaporation rate.

The cone angle measurements showed no correlation with the fuel properties which were examined. The explanation for this might be in the technique used to take the high-speed movies. This technique involved backlighting of the spray so that the spray would appear as a dark shadow on the film. The backlighting technique typically is used to detect the dense liquid phase core of the fuel spray.(14) It is not expected that using this technique would allow accurate definition of the less dense fringes of the spray. The fringe area would be affected by the degree of atomization which is fuel dependent. Other lighting techniques (14) have been used to detect the less dense liquid phase and vapor phase fuel. These techniques may provide a better method for determining the cone angle of the fuel sprays.

B. Cummins Injector

The effect of viscosity on the penetration rate for the Cummins PT injector was opposite the effect in the pintle injector. In the Cummins, as viscosity increased, the penetration rate increased. The viscosity effect was relatively large with the tip penetration rate of the most viscous fuel being more than four times the penetration rate of the base fuel. This would indicate that the more viscous fuels would have a greater probability of impingement, particularly if the drop-size distribution follows the same trend as in the pintle injector. Unfortunately, drop-size information was not obtained for this injector and would be difficult to acquire due to the nature of the spray as described previously.

C. DDA/53 and DDA/71 Injectors

As indicated previously, the fuel sprays from the Detroit Diesel injectors were themselves very similar in nature but had significantly different spray characteristics than the Cummins or pintle injectors. The main difference was the presence of two distinct flow regions of the fuel spray. The fuel spray began as a solid core of liquid coming out of the nozzle orifice. The liquid core eventually broke into drops due to air entrainment. The length at which the break-up occurred was shown to be related to the fuel viscosity for both nozzles. As fuel viscosity increased, the break-up length also increased. There was some scatter in this data indicating that the break-up length might be related to another parameter (i.e., surface tension) which was not investigated.

A change in the break-up length could affect engine performance. Certainly if the break-up occurred in a relatively short distance, there would be more time available for evaporation of the drops. A longer break-up length, therefore, could lead to fuel impingement or poor ignition. This naturally would depend upon the relationship between fuel viscosity and the drop-size distribution after break-up has occurred.

The cone angle of the spray for the DDA injectors was shown to decrease as viscosity increased. Examination of Figures 5 and 9 indicate the effect of viscosity on cone angle was very similar for the two DDA injectors. It was interesting to note that the cone angle decreased as viscosity increased from 5 to 14 cSt but then appeared to increase as viscosity increased from 14 to 23 cSt. For both injectors, therefore, there appears to be some curvature in the cone angle versus viscosity data.

It is hypothesized that this curvature is not a physical phenomena but a result of the technique used to obtain the high-speed movies and measure the cone angle. As previously indicated, the backlighting technique of taking the high-speed movies is generally used to detect the dense liquid phase core of the fuel spray.(14) Generally, the center of the fuel spray appears as a dark shadow in the high-speed movies with the area outside of the spray appearing white. These two regions, the center of the spray or completely out of the spray, are easily defined on the high-speed films. The fringes of the spray, however, generally appear less dark than the center and are, therefore, more difficult to define. The darkness of the fringes depends upon the degree of obscuration of the light. Through the center of the spray the light is totally obscured and thus it appears black. The obscuration of light at the fringe would be dependent upon size and concentration of the drops on the edge of the spray. It would be expected that the larger drops would have a greater effect on the light passing through them and provide a higher degree of obscuration, thus making the fringe area easier to define. Smaller drops would not obscure as much light and, therefore, a small drop-size distribution might lead to under estimating the actual cone angle.

The drop-size distribution would be expected to increase as viscosity increased. If there was a significant difference in viscosity and hence, drop-size distribution, for two fuels, there could be a considerable difference in the accuracy of the cone angle measurement for those fuels. The trend would naturally depend upon the drop concentration and its relationship with the fuel viscosity. However, it is possible that drop-size variations could induce a systematic error in the cone angle measurement.

The penetration rate after break-up was shown to be affected by viscosity for both DDA injectors. For the DDA/53 injector, an increase in viscosity decreased the penetration rate. The penetration rate increased for the DDA/71 injector as viscosity increased. An increase in penetration rate with an increase in viscosity would be the expected trend, particularly since cone angle was observed to decrease with an increase in viscosity. In general, a decrease in cone angle is accompanied by an increase in penetration rate.

VIII. SUMMARY AND CONCLUSIONS

The drop-size distribution and evaporation rate data are important spray characteristics in determining the effect of fuel property changes on engine performance. Fuel property effects on the spray characteristics which reflect drop-size distribution and evaporation rates were determined for four injection nozzles used extensively by the Navy. Viscosity was shown to effect the penetration rate, cone angle, and drop-size distribution. Specific gravity was not observed to have an effect on the above parameters.

Penetration data for the pintle nozzle were directly proportional to time. Comparison of the rate of penetration for each fuel indicated that as viscosity increased, the penetration rate decreased. The changes in fuel viscosity had no observable effect on the cone angle. The lighting technique (backlighting) used for obtaining the high-speed movies was not well suited for determination of the spray cone angle.

Drop-size measurements were successfully made on the fuel spray from the pintle nozzle. An increase in viscosity resulted in an increase in the drop-size distribution. The Sauter Mean Diameter (SMD) of the fuel spray was observed to increase from 6.5 micrometers at a viscosity of 3.0 centistokes to 12.5 micrometers at 35 centistokes. Since droplet evaporation times are proportional to the drop diameter squared, this increase would be expected to have a large impact on fuel-air mixing and combustion.

Changes in viscosity had a large effect on the penetration rate for the Cummins injector. The penetration rate increased from 20 mm/msec to 75 mm/msec as the fuel viscosity was increased from 3.0 centistokes to 40 centistokes. At viscosities above 10 centistokes, an increase in viscosity resulted in a decrease in the cone angle of the fuel spray. For viscosities below 10 centistokes an increase in viscosity appeared to result in an increase in cone angle. The lighting technique would again be expected to affect the measured cone angle particularly at the lower viscosities where atomization is good and the drop sizes are small.

The spray characteristics of the Detroit Diesel injectors were very similar. These injectors differ from the pintle and Cummins injectors in that two distinct flow regions can be identified. The transition from one region to the other is characterized by a break-up length. Prior to the break-up length the spray exists as a solid liquid jet; air entrainment leads to break-up of the jet into drops. A relatively long break-up length would indicate poor air-fuel mixing and would lead to poor ignition and combustion.

Several spray parameters were determined for fuel-to-fuel comparisons. These were the initial penetration rate, the break-up length, and the penetration rate after break-up. The initial penetration rate was not found to be related to the viscosity of the fuel for either injector. The viscosity did, however, appear to affect the jet break-up length; as viscosity increased, the jet break-up length increased. Since the break-up length is one parameter which characterizes atomization, an increase in the break-up length would be expected to affect fuel-air mixing, ignition, and combustion. The magnitude of this effect cannot be determined from the spray data.

The penetration rate after break-up was affected by the visocisty. For the DDA/53 injector an increase in viscosity resulted in a decrease in the penetration rate after break-up. An increase in viscosity increased the penetration rate after break-up for the DDA/71 injector. The cone angle of the fuel spray for both injectors was found to decrease as viscosity increased.

IX. RECOMMENDATIONS

Drop-size measurements at elevated temperatures need to be made for the different fuel-nozzle combinations. Different lighting techniques for taking high-speed movies of the injection process need to be examined for obtaining the most information on the spray fringe area. Combustion experiments are required to quantify the effect of break-up length on ignition and combustion.

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APPENDIX A

PENETRATION VERSUS TIME DATA FOR EACH TEST FUEL FOR THE PINTLE INJECTOR

FILM NUMBER:	030601	SPECIFIC GRAVITY:	.8445
FUEL NUMBER:	DF2	FUEL TEMPERATURE, C:	30.0
NOZZLE TYPE:	PINTLE	FUEL FLOW, mL/1000 Stk:	24.1
VISCOSITY, cSt:	3.79		

INJECTION NUMBER 2		INJECTION NUMBER 3		INJECTION NUMBER 4	
TIME (ms)	PENETRATION (mm)	TIME (ms)	PENETRATION (mm)	TIME (ms)	PENETRATION (mm)
42.36	5.04	39.42	4.14	36.97	4.10
82.74	8.49	79.79	6.85	77.34	6.81
123.11	12.59	120.17	10.78	117.72	10.30
163.49	16.66	160.54	15.12	158.09	14.61
203.86	20.72	200.92	18.92	198.47	18.78
244.24	25.01	241.29	23.56	238.84	22.38
284.61	29.36	281.67	27.73	279.22	27.64
324.99	33.37	322.04	32.42	319.59	31.97
365.36	37.51	362.42	36.03	359.97	36.28
405.74	42.31	402.79	41.18	400.34	40.77
446.11	46.26	443.17	45.03	440.72	44.88
486.49	49.65	483.54	48.42	481.09	48.09

FILM NUMBER:	030801	SPECIFIC GRAVITY:	.8488
FUEL NUMBER:	DFM	FUEL TEMPERATURE, C:	30.0
NOZZLE TYPE:	PINTLE	FUEL FLOW, mL/1000 Stk:	23.6
VISCOSITY, cSt:	3.46		

INJECTION NUMBER 2		INJECTION NUMBER 3		INJECTION NUMBER 4	
TIME (ms)	PENETRATION (mm)	TIME (ms)	PENETRATION (mm)	TIME (ms)	PENETRATION (mm)
33.45	4.68	56.05	5.05	36.98	3.61
70.87	6.82	93.47	9.93	74.41	5.71
108.30	10.39	130.90	13.84	111.83	9.81
145.72	14.03	168.32	18.71	149.26	13.33
183.15	19.79	205.75	20.45	186.68	17.61
220.57	25.00	243.17	23.94	224.11	21.80
258.00	28.65	280.60	26.97	261.53	26.92
295.42	32.54	318.02	32.03	298.96	28.15
332.85	37.11	355.45	35.95	336.38	31.23
370.27	41.36	392.87	39.27	373.81	35.49
407.70	45.36	430.30	44.61	411.23	40.32
445.12	49.57	467.72	48.75	448.66	44.28
				486.08	48.35
				523.51	52.71

FILM NUMBER: 030802 SPECIFIC GRAVITY: .8745

FUEL NUMBER: HMGO FUEL TEMPERATURE, C: 30.0

NOZZLE TYPE: PINTLE FUEL FLOW, mL/1000 Stk: 24.3

VISCOSITY, cSt: 8.35

INJECTION NUMBER 2		INJECTION NUMBER 3		INJECTION NUMBER 4	
TIME (ms)	PENETRATION (mm)	TIME (ms)	PENETRATION (mm)	TIME (ms)	PENETRATION (mm)
35.60	4.25	28.55	3.55	38.64	3.96
75.70	7.40	68.65	6.00	78.74	7.35
115.80	11.37	108.75	9.89	118.84	11.74
155.90	15.40	148.85	14.91	158.94	15.37
196.00	19.43	188.95	19.14	199.04	20.15
236.10	24.43	229.05	23.56	239.14	23.96
276.20	29.08	269.15	26.82	279.24	29.23
316.30	33.05	309.25	31.30	319.34	33.46
356.40	38.68	349.35	36.13	359.44	37.18
396.50	42.54	389.45	39.44	399.54	42.52
436.60	46.75	429.55	43.60	439.64	46.75
476.70	51.03	469.65	47.90	479.74	50.70

FILM NUMBER:	030803	SPECIFIC GRAVITY:	.8745
FUEL NUMBER:	HMGO	FUEL TEMPERATURE, C:	28.0
NOZZLE TYPE:	PINTLE	FUEL FLOW, mL/1000 Stk:	24.3
VISCOSITY, cSt:	8.92		

INJECTION NUMBER 2		INJECTION NUMBER 3		INJECTION NUMBER 4	
TIME (ms)	PENETRATION (mm)	TIME (ms)	PENETRATION (mm)	TIME (ms)	PENETRATION (mm)
33.73	3.41	37.07	4.17	38.47	3.07
73.83	5.83	77.17	7.05	78.57	5.57
113.93	9.18	117.27	10.85	118.67	9.02
154.03	13.47	157.37	14.40	158.77	13.53
194.13	16.97	197.47	19.44	198.87	17.48
234.23	21.51	237.57	23.02	238.97	22.22
274.33	26.52	277.67	27.24	279.07	26.16
314.43	31.72	317.77	32.49	319.17	31.13
354.53	35.30	357.87	36.38	359.27	36.23
394.63	39.56	397.97	40.13	399.37	39.40
434.73	44.12	438.07	44.75	439.47	43.56
474.83	48.06	478.17	49.11	479.57	47.96
514.93	53.07			519.67	52.60

FILM NUMBER: 031101

FUEL NUMBER: BLEND 5

NOZZLE TYPE: PINTLE

VISCOSITY, cSt: 6.59

SPECIFIC GRAVITY: .8911

FUEL TEMPERATURE, C: 30.0

FUEL FLOW, mL/1000 Stk: 23.6

INJECTION NUMBER 2		INJECTION NUMBER 3		INJECTION NUMBER 4	
TIME (ms)	PENETRATION (mm)	TIME (ms)	PENETRATION (mm)	TIME (ms)	PENETRATION (mm)
39.45	4.42	32.06	3.86	40.15	4.66
79.70	7.51	72.31	6.19	80.40	7.93
119.95	12.35	112.56	10.29	120.65	12.59
160.20	16.19	152.81	13.70	160.90	15.94
200.45	20.09	193.06	18.71	201.15	20.64
240.70	24.26	233.31	23.12	241.40	24.33
280.95	28.62	273.56	28.16	281.65	28.19
321.20	33.27	313.81	31.87	321.90	32.92
361.45	36.65	354.06	35.49	362.15	37.54
401.70	41.00	394.31	40.12	402.40	41.39
441.95	45.88	434.56	44.49	442.65	46.35
482.20	49.89	474.81	48.32	482.90	50.45

FILM NUMBER: 031102

FUEL NUMBER: BLEND 6

NOZZLE TYPE: PINTLE

VISCOSITY, cSt: 20.60

SPECIFIC GRAVITY: .8571

FUEL TEMPERATURE, C: 28.0

FUEL FLOW, mL/1000 Stk: 23.1

INJECTION NUMBER 2		INJECTION NUMBER 3		INJECTION NUMBER 4	
TIME (ms)	PENETRATION (mm)	TIME (ms)	PENETRATION (mm)	TIME (ms)	PENETRATION (mm)
35.75	4.17	39.83	3.60	36.36	3.99
75.90	6.04	79.98	6.84	76.51	6.59
116.05	7.32	120.13	10.12	116.66	9.71
156.20	10.66	160.28	13.20	156.81	12.68
196.35	13.96	200.43	16.92	196.96	16.04
236.50	17.24	240.58	20.75	237.11	20.56
276.65	21.51	280.73	24.41	277.26	24.39
316.80	25.48	320.88	28.33	317.41	28.36
356.95	29.77	361.03	32.51	357.56	31.47
397.10	33.92	401.18	37.14	397.71	35.66
437.25	38.92	441.33	41.79	437.86	40.10
477.40	43.11	481.48	46.52	478.01	44.77
517.55	47.43	521.63	51.54	518.16	49.73

FILM NUMBER:	031103	SPECIFIC GRAVITY:	.8927
FUEL NUMBER:	BLEND 8	FUEL TEMPERATURE, C:	28.0
NOZZLE TYPE:	PINTLE	FUEL FLOW, mL/1000 Stk:	23.1
VISCOSITY, cSt:	19.63		

INJECTION NUMBER 2		INJECTION NUMBER 3		INJECTION NUMBER 4	
TIME (ms)	PENETRATION (mm)	TIME (ms)	PENETRATION (mm)	TIME (ms)	PENETRATION (mm)
38.14	4.59	35.69	4.03	40.00	3.96
78.39	6.10	75.94	4.43	80.25	5.48
118.64	10.02	116.19	9.04	120.50	8.23
158.89	12.92	156.44	12.85	160.75	11.99
199.14	16.88	196.69	15.30	201.00	14.78
239.39	20.48	236.94	18.92	241.25	18.33
279.64	24.74	277.19	23.46	281.50	21.87
319.89	28.25	317.44	27.34	321.75	25.90
360.14	32.82	357.69	31.23	362.00	30.18
400.39	37.05	397.94	35.34	402.25	34.26
440.64	41.73	438.19	39.73	442.50	38.67
480.89	45.96	478.44	44.22	482.75	42.93
521.14	50.02	518.69	47.95	523.00	47.18
561.39	54.11	558.94	52.74	563.25	51.07

FILM NUMBER: 031201

FUEL NUMBER: BLEND 9

NOZZLE TYPE: PINTLE

VISCOSITY, cSt: 35.02

SPECIFIC GRAVITY: .8586

FUEL TEMPERATURE, C: 27.0

FUEL FLOW, mL/1000 Stk: 24.7

INJECTION NUMBER 2		INJECTION NUMBER 3		INJECTION NUMBER 4	
TIME (ms)	PENETRATION (mm)	TIME (ms)	PENETRATION (mm)	TIME (ms)	PENETRATION (mm)
39.68	4.66	39.37	3.48	39.15	4.03
80.68	7.64	80.37	7.11	80.15	6.03
121.68	10.99	121.37	10.40	121.15	8.78
162.68	14.55	162.37	13.45	162.15	12.09
203.68	18.35	203.37	17.27	203.15	15.61
244.68	22.36	244.37	20.89	244.15	18.91
285.68	26.35	285.37	24.36	285.15	22.66
326.68	31.43	326.37	28.82	326.15	26.75
367.68	35.74	367.37	33.20	367.15	31.72
408.68	40.81	408.37	37.39	408.15	36.48
449.68	45.79	449.37	42.49	449.15	41.10
490.68	50.08	490.37	46.41	490.15	45.59
531.68	53.69	531.37	50.75	531.15	49.85
				572.15	55.07

FILM NUMBER:	031202	SPECIFIC GRAVITY:	.8899
FUEL NUMBER:	BLEND 11	FUEL TEMPERATURE, C:	30.0
NOZZLE TYPE:	PINTLE	FUEL FLOW, mL/1000 Stk:	23.6
VISCOSITY, cSt:	29.86		

INJECTION NUMBER 2		INJECTION NUMBER 3		INJECTION NUMBER 4	
TIME (ms)	PENETRATION (mm)	TIME (ms)	PENETRATION (mm)	TIME (ms)	PENETRATION (mm)
35.93	4.20	38.68	3.50	31.89	2.88
76.15	7.27	78.90	6.12	72.11	4.91
116.38	10.38	119.13	9.58	112.34	7.78
156.60	13.70	159.35	12.65	152.56	11.61
196.83	17.08	199.58	16.10	192.79	15.21
237.05	21.12	239.80	19.63	233.01	18.10
277.28	25.02	280.03	23.59	273.24	21.04
317.50	30.15	320.25	27.64	313.46	25.20
357.73	34.94	360.48	31.47	353.69	29.99
397.95	39.28	400.70	35.66	393.91	34.26
438.18	43.85	440.93	40.03	434.14	38.82
478.40	47.96	481.15	45.10	474.36	44.51
518.63	51.47	521.38	49.67	514.59	47.52
		561.60	53.99	554.81	51.80

FILM NUMBER: 031203

FUEL NUMBER: BLEND 13

NOZZLE TYPE: PINTLE

VISCOSITY, cSt: 6.36

SPECIFIC GRAVITY: .8251

FUEL TEMPERATURE, C: 30.0

FUEL FLOW, mL/1000 Stk: 23.9

INJECTION NUMBER 2		INJECTION NUMBER 3		INJECTION NUMBER 4	
TIME (ms)	PENETRATION (mm)	TIME (ms)	PENETRATION (mm)	TIME (ms)	PENETRATION (mm)
40.18	3.44	34.46	4.14	39.41	3.60
80.46	6.02	74.74	6.52	79.68	6.68
120.73	9.79	115.01	10.25	119.96	9.97
161.01	13.33	155.29	13.89	160.23	13.96
201.28	18.66	195.56	17.60	200.51	19.14
241.56	22.55	235.84	22.59	240.78	23.15
281.83	27.30	276.11	26.94	281.06	27.05
322.11	31.53	316.39	31.73	321.33	31.93
362.38	36.03	356.66	35.77	361.61	38.85
402.66	39.90	396.94	39.07	401.88	44.87
442.93	44.32	437.21	44.22	442.16	49.46
483.21	48.16	477.49	49.20	482.43	53.24

FILM NUMBER: 040401

FUEL NUMBER: BLEND 13

NOZZLE TYPE: PINTLE

VISCOSITY, cSt: 6.36

SPECIFIC GRAVITY: .8251

FUEL TEMPERATURE, C: 30.0

FUEL FLOW, mL/1000 Stk: 23.9

INJECTION NUMBER 2		INJECTION NUMBER 3	
TIME (ms)	PENETRATION (mm)	TIME (ms)	PENETRATION (mm)
25.99	2.46	24.26	3.17
66.26	6.27	64.53	6.30
106.54	11.79	104.81	11.80
146.81	15.53	145.08	14.92
187.09	20.07	185.36	19.43
227.36	23.51	225.63	24.05
267.64	27.80	265.91	27.72
307.91	32.54	306.18	32.49
348.19	36.77	346.46	36.58
388.46	40.71	386.73	41.04
428.74	44.82	427.01	45.83
469.01	48.57	467.28	50.68
509.29	53.37	507.56	55.16

FILM NUMBER: 040402

FUEL NUMBER: DF2

NOZZLE TYPE: PINTLE

VISCOSITY, cSt: 3.79

SPECIFIC GRAVITY: .8445

FUEL TEMPERATURE, C: 30.0

FUEL FLOW, mL/1000 Stk: 24.6

INJECTION NUMBER 2		INJECTION NUMBER 3	
TIME (ms)	PENETRATION (mm)	TIME (ms)	PENETRATION (mm)
36.46	4.16	36.70	3.02
76.83	7.54	77.08	6.35
117.21	12.55	117.45	9.71
157.58	16.91	157.83	13.63
197.96	20.48	198.20	18.64
238.33	23.53	238.58	23.28
278.71	28.42	278.95	28.68
319.08	33.03	319.33	31.66
359.46	38.55	359.70	35.74
399.83	42.95	400.08	40.80
440.21	46.88	440.45	44.80
480.58	51.07	480.83	49.21
520.96	55.04	521.20	53.27

APPENDIX B

PENETRATION VERSUS TIME DATA FOR EACH TEST FUEL FOR THE DDA/53 INJECTION SYSTEM

FILM NUMBER:	113001	SPECIFIC GRAVITY:	.8927
FUEL NUMBER:	BLEND 8	FUEL TEMPERATURE, C:	36.0
NOZZLE TYPE:	DDA_53	FUEL FLOW, mL/1000 Stk:	60.4
VISCOSITY, cSt:	14.25		

INJECTION NUMBER 2		INJECTION NUMBER 3		INJECTION NUMBER 4	
TIME (ms)	PENETRATION (mm)	TIME (ms)	PENETRATION (mm)	TIME (ms)	PENETRATION (mm)
19.20	3.34	25.38	2.70	38.56	3.28
59.68	10.39	65.86	4.33	79.04	5.49
100.15	12.96	106.33	8.74	119.51	7.23
140.63	15.67	146.81	12.11	159.99	9.10
181.10	17.73	187.28	17.23	200.46	12.06
221.58	19.95	227.76	20.13	240.94	15.11
262.05	22.88	268.23	23.44	281.41	18.77
302.53	24.76	308.71	26.85	321.89	22.75
343.00	26.16	349.18	29.44	362.36	25.22
383.48	28.65	389.66	30.68	402.84	27.60
423.95	30.47	430.13	32.70	443.31	30.32
464.43	32.22	470.61	35.14	483.79	32.78
504.90	33.66	511.08	37.12	524.26	35.19
545.38	34.91	551.56	38.65	564.73	37.55
585.85	36.27	592.03	40.43	605.21	39.74
626.33	37.14	632.51	42.28	645.69	41.63
666.80	38.40	672.98	44.05	686.16	42.27
707.28	39.56	713.46	45.09	726.64	43.84
747.75	41.40	753.93	45.78	767.11	46.46
788.23	42.19	794.41	47.04	807.59	48.30
828.70	43.50	834.88	49.12	848.06	50.18
869.18	44.33	875.36	50.97	888.54	52.53

FILM NUMBER: 113002

FUEL NUMBER: DF2

NOZZLE TYPE: DDA_53

VISCOSITY, cSt: 3.29

SPECIFIC GRAVITY: .8445

FUEL TEMPERATURE, C: 36.0

FUEL FLOW, mL/1000 Stk: 60.7

INJECTION NUMBER 2		INJECTION NUMBER 3	
TIME (ms)	PENETRATION (mm)	TIME (ms)	PENETRATION (mm)
12.79	7.57	19.35	11.93
53.26	11.82	59.83	14.57
93.74	17.37	100.30	19.73
134.21	21.93	140.78	23.86
174.69	24.99	181.26	25.58
215.16	27.86	221.73	27.45
255.64	28.86	262.21	29.60
296.11	30.06	302.68	31.21
336.59	31.29	343.16	33.09
377.06	32.12	383.63	35.55
417.54	33.76	424.11	37.22
458.01	35.16	464.58	38.84
498.49	36.32	505.05	39.43
538.96	37.15	545.53	40.04
579.44	39.24	586.01	41.56
619.91	40.29	626.48	42.84
660.39	41.27	666.96	44.32
700.86	42.76	707.43	45.27
741.34	44.38	747.91	47.37
781.81	45.30	788.38	48.17
822.29	46.46	828.86	49.55

FILM NUMBER:	120301	SPECIFIC GRAVITY:	.8488
FUEL NUMBER:	DFM	FUEL TEMPERATURE, C:	36.0
NOZZLE TYPE:	DDA_53	FUEL FLOW, mL/1000 Stk:	60.6
VISCOSITY, cSt:	3.02		

INJECTION NUMBER 2		INJECTION NUMBER 3		INJECTION NUMBER 4	
TIME (ms)	PENETRATION (mm)	TIME (ms)	PENETRATION (mm)	TIME (ms)	PENETRATION (mm)
27.46	1.59	30.36	3.88	25.38	3.28
67.93	3.93	70.83	7.13	65.85	8.51
108.41	8.36	111.31	12.72	106.33	13.03
148.88	14.00	151.78	16.50	146.80	15.88
189.36	18.39	192.26	19.47	187.28	19.44
229.83	22.17	232.73	22.67	227.75	21.63
270.31	24.83	273.21	24.72	268.23	23.80
310.78	27.11	313.68	26.01	308.70	25.14
351.26	27.75	354.16	27.75	349.18	26.88
391.73	28.62	394.63	29.06	389.65	28.76
432.21	30.12	435.11	32.01	430.13	30.35
472.68	31.88	475.58	34.84	470.60	32.76
513.16	33.16	516.06	37.14	511.08	34.78
553.63	34.12	556.53	39.25	551.55	36.37
594.11	36.12	597.01	40.09	592.03	38.27
634.58	37.11	637.48	40.86	632.50	40.20
675.06	37.97	677.96	41.56	672.98	41.69
715.53	38.88	718.43	42.38	713.45	43.25
756.01	39.76	758.91	43.45	753.93	44.64
796.48	40.88	799.38	44.14	794.40	45.51
836.96	42.55	839.86	45.38	834.88	46.58
877.43	44.25	880.33	46.12	875.35	47.48
917.91	45.63	920.81	46.78	915.83	48.82
958.38	47.28	961.28	47.56	956.30	50.33
998.86	48.25	1001.76	48.92	996.78	51.25

FILM NUMBER:	120302	SPECIFIC GRAVITY:	.8745
FUEL NUMBER:	HMGO	FUEL TEMPERATURE, C:	36.0
NOZZLE TYPE:	DDA_53	FUEL FLOW, mL/1000 Stk:	61.0
VISCOSITY, cSt:	6.94		

INJECTION NUMBER 2		INJECTION NUMBER 3		INJECTION NUMBER 4	
TIME (ms)	PENETRATION (mm)	TIME (ms)	PENETRATION (mm)	TIME (ms)	PENETRATION (mm)
10.72	1.02	22.27	1.70	34.23	3.93
51.20	4.85	62.75	4.80	74.71	6.39
91.67	10.39	103.22	7.78	115.18	9.95
132.15	13.90	143.70	11.14	155.66	13.14
172.62	16.46	184.17	14.60	196.13	18.45
213.10	19.22	224.65	18.59	236.61	20.45
253.57	22.17	265.12	20.91	277.08	24.34
294.05	24.40	305.60	23.19	317.56	26.60
334.52	26.03	346.07	25.13	358.03	27.80
375.00	27.60	386.55	27.01	398.51	29.01
415.47	29.40	427.02	29.12	438.98	29.71
455.95	32.06	467.50	31.63	479.46	31.94
496.42	34.09	507.97	33.55	519.93	34.35
536.90	35.29	548.45	35.25	560.41	36.20
577.37	37.11	588.92	36.29	600.88	37.20
617.85	38.66	629.40	37.19	641.36	38.65
658.32	39.97	669.87	38.73	681.83	40.32
698.80	41.27	710.35	39.56	722.31	42.61
739.27	41.79	750.82	40.60	762.78	44.05
779.75	41.96	791.30	41.65	803.26	44.97
820.22	44.22	831.77	42.38	843.73	45.71
860.70	45.22	872.25	43.28	884.21	46.32
901.17	46.41	912.72	43.86	924.68	46.84
941.65	47.61	953.20	45.58	965.16	47.43
982.12	49.45	993.67	45.79	1005.63	48.28
1022.60	51.28			1046.11	49.81
				1086.58	50.63
				1127.06	51.66

FILM NUMBER:	120303	SPECIFIC GRAVITY:	.8586
FUEL NUMBER:	BLEND 9	FUEL TEMPERATURE, C:	36.0
NOZZLE TYPE:	DDA_53	FUEL FLOW, mL/1000 Stk:	63.0
VISCOSITY, cSt:	23.05		

INJECTION NUMBER 2		INJECTION NUMBER 3		INJECTION NUMBER 4	
TIME (ms)	PENETRATION (mm)	TIME (ms)	PENETRATION (mm)	TIME (ms)	PENETRATION (mm)
20.96	2.84	-5.17	.95	26.46	2.75
61.44	8.31	35.31	1.39	66.93	6.97
101.91	12.98	75.78	6.33	107.41	12.37
142.39	16.75	116.26	12.00	147.88	17.37
182.86	20.67	156.73	16.65	188.36	21.14
223.34	24.76	197.21	20.59	228.83	25.44
263.81	26.80	237.68	25.44	269.31	28.45
304.29	28.55	278.16	28.63	309.78	30.94
344.76	30.19	318.63	30.30	350.26	33.40
385.24	31.91	359.11	29.80	390.73	32.07
425.71	33.88	399.58	30.96	431.21	33.57
466.19	35.02	440.06	32.50	471.68	35.34
506.66	37.15	480.53	35.45	512.16	36.96
547.14	38.42	521.01	37.68	552.63	38.40
587.61	40.43	561.48	39.83	593.11	40.02
628.09	41.78	601.96	41.65	633.58	42.61
668.56	43.01	642.43	43.30	674.06	44.14
709.04	44.42	682.91	44.38	714.53	44.94
749.51	45.94	723.38	45.73	755.01	46.30
789.99	47.17	763.86	47.40	795.48	47.46
830.46	48.15	804.33	47.73	835.96	46.07
870.94	49.71	844.81	48.27	876.43	47.27
911.41	50.81	885.28	49.71	916.91	48.18
		925.76	51.27	957.38	49.12
				997.86	50.56

FILM NUMBER:	120401	SPECIFIC GRAVITY:	.8586
FUEL NUMBER:	BLEND 9	FUEL TEMPERATURE, C:	36.0
NOZZLE TYPE:	DDA_53	FUEL FLOW, mL/1000 Stk:	63.0
VISCOSITY, cSt:	23.05		

INJECTION NUMBER 2		INJECTION NUMBER 3		INJECTION NUMBER 4	
TIME (ms)	PENETRATION (mm)	TIME (ms)	PENETRATION (mm)	TIME (ms)	PENETRATION (mm)
32.05	2.87	12.65	1.31	11.74	1.61
72.53	6.49	53.12	5.51	52.21	7.15
113.00	10.77	93.60	10.08	92.69	11.03
153.48	14.95	134.07	14.85	133.16	15.14
193.95	18.78	174.55	18.32	173.64	19.18
234.43	23.57	215.02	22.06	214.11	23.73
274.90	26.16	255.50	26.53	254.59	26.58
315.38	26.76	295.97	28.83	295.06	28.29
355.85	27.94	336.45	29.47	335.54	29.12
396.33	29.63	376.92	30.37	376.01	29.62
436.80	31.70	417.40	30.71	416.49	32.34
477.28	33.32	457.87	32.76	456.96	35.43
517.75	34.86	498.35	34.99	497.44	36.73
558.23	36.17	538.82	36.01	537.91	36.40
598.70	37.17	579.30	36.96	578.39	36.81
639.18	39.06	619.77	38.29	618.86	36.96
679.65	40.47	660.25	39.45	659.34	38.61
720.13	42.51	700.72	40.51	699.81	39.88
760.60	43.01	741.20	42.19	740.29	41.14
801.08	43.35	781.67	43.20	780.76	43.19
841.55	44.45	822.15	43.30	821.24	44.68
882.03	45.33	862.62	43.96	861.71	46.04
922.50	46.37	903.10	44.76	902.19	47.64
962.98	46.19	943.57	45.78	942.66	49.17
1003.45	46.97	984.05	46.84	983.14	50.33
1043.93	49.10	1024.52	47.53	1023.61	51.73

FILM NUMBER: 120402 | SPECIFIC GRAVITY: .8899

FUEL NUMBER: BLEND 11 | FUEL TEMPERATURE, C: 36.0

NOZZLE TYPE: DDA_53 | FUEL FLOW, mL/1000 Stk: 63.0

VISCOSITY, cSt: 22.76

INJECTION NUMBER 2		INJECTION NUMBER 3		INJECTION NUMBER 4	
TIME (ms)	PENETRATION (mm)	TIME (ms)	PENETRATION (mm)	TIME (ms)	PENETRATION (mm)
11.10	1.34	16.52	1.82	26.56	1.72
51.58	6.24	56.99	6.28	67.04	4.34
92.05	10.67	97.47	12.44	107.51	9.75
132.53	13.73	137.94	15.95	147.99	12.80
173.00	17.14	178.42	18.88	188.46	17.77
213.48	20.65	218.89	22.42	228.94	21.85
253.95	22.47	259.37	24.58	269.41	24.42
294.43	25.08	299.84	27.50	309.89	27.88
334.90	26.16	340.32	30.47	350.36	29.57
375.38	27.98	380.79	32.43	390.84	31.84
415.85	29.19	421.27	33.53	431.31	33.48
456.33	31.62	461.74	35.27	471.79	35.24
496.80	33.14	502.22	37.22	512.26	36.73
537.28	34.84	542.69	38.71	552.74	37.60
577.75	36.12	583.17	39.88	593.21	38.81
618.23	37.40	623.64	40.89	633.69	40.04
658.70	38.29	664.12	41.88	674.16	41.02
699.18	39.53	704.59	42.43	714.64	42.47
739.65	40.92	745.07	43.58	755.11	44.01
780.13	42.28	785.54	44.92	795.59	45.07
820.60	43.10	826.02	45.71	836.06	45.97
861.08	44.68	866.49	47.17	876.54	48.53
901.55	45.61	906.97	48.35	917.01	47.86
942.03	47.02	947.44	49.68	957.49	49.63
982.50	48.51	987.92	50.89	997.96	51.95

FILM NUMBER:	120403	SPECIFIC GRAVITY:	.8251
FUEL NUMBER:	BLEND 13	FUEL TEMPERATURE, C:	36.0
NOZZLE TYPE:	DDA_53	FUEL FLOW, mL/1000 Stk:	60.3
VISCOSITY, cSt:	5.37		

INJECTION NUMBER 2		INJECTION NUMBER 3		INJECTION NUMBER 4	
TIME (ms)	PENETRATION (mm)	TIME (ms)	PENETRATION (mm)	TIME (ms)	PENETRATION (mm)
32.31	3.11	21.81	2.52	37.31	4.36
72.79	7.01	62.28	4.77	77.78	7.39
113.26	10.31	102.76	9.51	118.26	12.62
153.74	15.85	143.23	14.87	158.73	16.80
194.21	20.80	183.71	19.93	199.21	22.13
234.69	24.21	224.18	24.19	239.68	25.88
275.16	25.13	264.66	26.76	280.16	28.11
315.64	27.04	305.13	27.96	320.63	29.86
356.11	28.71	345.61	28.81	361.11	28.63
396.59	29.93	386.08	30.14	401.58	30.96
437.06	32.39	426.56	33.39	442.06	33.84
477.54	34.14	467.03	35.29	482.53	36.11
518.01	34.94	507.51	37.47	523.01	37.40
558.49	34.19	547.98	39.07	563.48	38.74
598.96	34.48	588.46	40.22	603.96	39.43
639.44	36.52	628.93	40.74	644.43	40.92
679.91	38.24	669.41	41.35	684.91	42.02
720.39	39.89	709.88	42.20	725.38	43.35
760.86	41.79	750.36	42.73	765.86	44.58
801.34	42.30	790.83	43.86	806.33	46.56
841.81	42.92	831.31	44.60	846.81	47.48
882.29	43.74	871.78	45.09	887.28	48.59
922.76	44.83	912.26	47.58	927.76	50.50
963.24	45.89	952.73	49.20	968.23	52.12

FILM NUMBER:	120701	SPECIFIC GRAVITY:	.8911
FUEL NUMBER:	BLEND 5	FUEL TEMPERATURE, C:	36.0
NOZZLE TYPE:	DDA_53	FUEL FLOW, mL/1000 Stk:	62.3
VISCOSITY, cSt:	5.55		

INJECTION NUMBER 2		INJECTION NUMBER 3		INJECTION NUMBER 4	
TIME (ms)	PENETRATION (mm)	TIME (ms)	PENETRATION (mm)	TIME (ms)	PENETRATION (mm)
7.57	1.00	26.19	3.65	9.89	1.28
48.04	6.32	66.66	9.29	50.37	6.51
88.52	11.40	107.14	14.57	90.84	13.00
128.99	14.24	147.61	18.52	131.32	18.61
169.47	18.37	188.09	20.76	171.79	21.34
209.94	22.56	228.56	24.18	212.27	23.82
250.42	25.03	269.04	26.44	252.74	25.41
290.89	26.56	309.51	28.71	293.22	27.45
331.37	27.70	349.99	30.04	333.69	28.98
371.84	28.95	390.46	31.47	374.17	30.64
412.32	30.90	430.94	33.83	414.64	31.88
452.79	33.48	471.41	35.87	455.12	33.71
493.27	35.58	511.89	38.07	495.59	36.49
533.74	37.19	552.36	39.49	536.07	38.02
574.22	39.24	592.84	41.29	576.54	39.88
614.69	40.70	633.31	42.49	617.02	41.43
655.17	41.79	673.79	44.35	657.49	42.67
695.64	43.22	714.26	45.79	697.97	44.25
736.12	44.60	754.74	46.77	738.44	45.94
776.59	45.19	795.21	47.98	778.92	47.44
817.07	46.39	835.69	49.36	819.39	49.19
857.54	47.52	876.16	50.27	859.87	50.52
898.02	48.43	916.64	51.53	900.34	51.97

FILM NUMBER:	120702	SPECIFIC GRAVITY:	.8571
FUEL NUMBER:	BLEND 6	FUEL TEMPERATURE, C:	36.0
NOZZLE TYPE:	DDA_53	FUEL FLOW, mL/1000 Stk:	62.5
VISCOSITY, cSt:	14.89		

INJECTION NUMBER 2		INJECTION NUMBER 3		INJECTION NUMBER 4	
TIME (ms)	PENETRATION (mm)	TIME (ms)	PENETRATION (mm)	TIME (ms)	PENETRATION (mm)
19.14	1.16	38.32	2.66	31.83	3.32
59.62	3.62	78.79	5.46	72.31	6.42
100.09	7.49	119.27	10.49	112.78	10.95
140.57	11.82	159.74	15.07	153.26	16.18
181.04	16.17	200.22	19.45	193.73	21.88
221.52	19.65	240.69	23.93	234.21	26.19
261.99	23.68	281.17	26.82	274.68	28.96
302.47	26.80	321.64	28.78	315.16	28.80
342.94	27.20	362.12	30.16	355.63	29.23
383.42	28.10	402.59	28.80	396.11	30.97
423.89	28.93	443.07	29.76	436.58	33.23
464.37	31.34	483.54	32.22	477.06	35.75
504.84	33.54	524.02	33.86	517.53	38.17
545.32	34.59	564.49	35.22	558.01	40.08
585.79	35.95	604.97	36.83	598.48	40.85
626.27	37.31	645.44	38.77	638.96	41.58
666.74	39.44	685.92	40.40	679.43	42.02
707.22	40.60	726.39	41.88	719.91	42.89
747.69	41.81	766.87	42.12	760.38	44.02
788.17	42.14	807.34	43.07	800.86	45.23
828.64	42.67	847.82	44.17	841.33	45.66
869.12	43.42	888.29	45.84	881.81	46.52
909.59	44.33	928.77	47.73	922.28	47.87
950.07	45.64	969.24	49.13	962.76	49.01
		1009.72	50.62	1003.23	51.20
		1050.19	52.15	1043.71	52.48

APPENDIX C

PENETRATION VERSUS TIME DATA FOR EACH TEST FUEL FOR THE DDA/71 INJECTION SYSTEM

FILM NUMBER:	052801	SPECIFIC GRAVITY:	.8445
FUEL NUMBER:	DF2	FUEL TEMPERATURE, C:	39.0
NOZZLE TYPE:	DDA_71	FUEL FLOW, mL/1000 Stk:	97.0
VISCOSITY, cSt:	3.09		

INJECTION NUMBER 2		INJECTION NUMBER 3	
TIME (ms)	PENETRATION (mm)	TIME (ms)	PENETRATION (mm)
25.81	2.31	21.90	1.82
65.71	5.89	61.80	5.13
105.61	10.52	101.70	9.23
145.51	14.32	141.60	12.58
185.41	17.95	181.50	14.98
225.31	20.95	221.40	18.61
265.21	24.11	261.30	23.17
305.11	27.24	301.20	25.80
345.01	29.99	341.10	28.15
384.91	31.42	381.00	29.61
424.81	33.20	420.90	31.43
464.71	34.74	460.80	33.31
504.61	37.02	500.70	34.85
		540.60	36.36

FILM NUMBER:	061901	SPECIFIC GRAVITY:	.8488
FUEL NUMBER:	DFM	FUEL TEMPERATURE, C:	39.0
NOZZLE TYPE:	DDA_71	FUEL FLOW, mL/1000 Stk:	100.5
VISCOSITY, cSt:	2.84		

INJECTION NUMBER 2		INJECTION NUMBER 3	
TIME (ms)	PENETRATION (mm)	TIME (ms)	PENETRATION (mm)
27.83	1.98	33.07	2.74
67.73	4.82	72.97	6.04
107.63	9.11	112.87	10.49
147.53	13.45	152.77	15.24
187.43	18.38	192.67	19.44
227.33	21.99	232.57	22.94
267.23	24.21	272.47	24.34
307.13	26.55	312.37	27.89
347.03	28.07	352.27	29.41
386.93	29.77	392.17	30.06
426.83	30.61	432.07	31.11
466.73	32.57	471.97	32.90
506.63	33.65	511.87	35.05
546.53	34.50	551.77	35.77

FILM NUMBER: 061902 SPECIFIC GRAVITY: .8745

FUEL NUMBER: HMGO FUEL TEMPERATURE, C: 39.0

NOZZLE TYPE: DDA_71 FUEL FLOW, mL/1000 Stk: 105.1

VISCOSITY, cSt: 6.36

INJECTION NUMBER 2		INJECTION NUMBER 3	
TIME (ms)	PENETRATION (mm)	TIME (ms)	PENETRATION (mm)
21.25	1.48	17.68	1.14
61.15	4.27	57.58	3.72
101.05	8.25	97.48	7.89
140.95	12.95	137.38	11.98
180.85	17.56	177.28	16.77
220.75	21.78	217.18	21.21
260.65	24.93	257.08	24.95
300.55	28.12	296.98	28.71
340.45	30.18	336.88	31.52
380.35	32.37	376.78	33.66
420.25	34.10	416.68	34.39
460.15	35.30	456.58	36.26

FILM NUMBER:	061903	SPECIFIC GRAVITY:	.8911
FUEL NUMBER:	BLEND 5	FUEL TEMPERATURE, C:	38.0
NOZZLE TYPE:	DDA_71	FUEL FLOW, mL/1000 Stk:	106.1
VISCOSITY, cSt:	5.26		

INJECTION NUMBER 2		INJECTION NUMBER 3	
TIME (ms)	PENETRATION (mm)	TIME (ms)	PENETRATION (mm)
32.23	3.39	25.44	2.22
72.13	7.60	65.34	5.71
112.03	11.78	105.24	9.84
151.93	15.79	145.14	14.20
191.83	19.81	185.04	19.59
231.73	23.76	224.94	23.65
271.63	26.95	264.84	26.96
311.53	29.11	304.74	30.30
351.43	30.45	344.64	32.54
391.33	32.32	384.54	34.02
431.23	34.00	424.44	35.72

FILM NUMBER: 061904

FUEL NUMBER: BLEND 6

NOZZLE TYPE: DDA_71

VISCOSITY, cSt: 14.89

SPECIFIC GRAVITY: .8571

FUEL TEMPERATURE, C: 36.0

FUEL FLOW, mL/1000 Stk: 103.2

INJECTION NUMBER 2		INJECTION NUMBER 3	
TIME (ms)	PENETRATION (mm)	TIME (ms)	PENETRATION (mm)
18.03	.81	18.49	2.57
57.93	2.60	58.39	8.10
97.83	10.34	98.29	12.08
137.73	14.49	138.19	16.80
177.63	18.62	178.09	20.47
217.53	23.00	217.99	24.95
257.43	27.29	257.89	27.05
297.33	29.38	297.79	29.47
337.23	31.10	337.69	30.72
377.13	32.61	377.59	32.73
417.03	34.98	417.49	35.24
456.93	36.90	457.39	36.76

FILM NUMBER:	062401	SPECIFIC GRAVITY:	.8927
FUEL NUMBER:	BLEND 8	FUEL TEMPERATURE, C:	38.0
NOZZLE TYPE:	DDA_71	FUEL FLOW, mL/1000 Stk:	101.5
VISCOSITY, cSt:	13.23		

INJECTION NUMBER 2		INJECTION NUMBER 3	
TIME (ms)	PENETRATION (mm)	TIME (ms)	PENETRATION (mm)
33.05	3.02	23.86	1.82
72.95	6.67	63.76	4.86
112.85	10.49	103.66	8.79
152.75	13.52	143.56	12.05
192.65	17.70	183.46	15.85
232.55	22.87	223.36	19.75
272.45	26.76	263.26	24.95
312.35	29.26	303.16	29.37
352.25	31.67	343.06	32.14
392.15	33.95	382.96	33.85
432.05	36.34	422.86	35.25

FILM NUMBER: 062402

FUEL NUMBER: BLEND 9

NOZZLE TYPE: DDA_71

VISCOSITY, cSt: 20.30

SPECIFIC GRAVITY: .8586

FUEL TEMPERATURE, C: 39.0

FUEL FLOW, mL/1000 Stk: 101.8

INJECTION NUMBER 2		INJECTION NUMBER 3	
TIME (ms)	PENETRATION (mm)	TIME (ms)	PENETRATION (mm)
23.05	1.62	28.33	1.98
62.95	4.41	68.23	4.77
102.85	8.17	108.13	8.26
142.75	12.18	148.03	11.86
182.65	15.96	187.93	17.15
222.55	22.09	227.83	22.26
262.45	26.97	267.73	28.03
302.35	29.59	307.63	29.79
342.25	31.89	347.53	31.13
382.15	34.67	387.43	33.04
422.05	36.99	427.33	34.78
461.95	38.84	467.23	37.09

FILM NUMBER:	062501	SPECIFIC GRAVITY:	.8899
FUEL NUMBER:	BLEND 11	FUEL TEMPERATURE, C:	36.0
NOZZLE TYPE:	DDA_71	FUEL FLOW, mL/1000 Stk:	104.3
VISCOSITY, cSt:	22.76		

INJECTION NUMBER 2		INJECTION NUMBER 3	
TIME (ms)	PENETRATION (mm)	TIME (ms)	PENETRATION (mm)
27.19	2.33	22.51	1.33
67.09	5.76	62.41	3.70
106.99	8.90	102.31	7.20
146.89	13.22	142.21	11.11
186.79	17.60	182.11	14.65
226.69	23.74	222.01	20.65
266.59	29.00	261.91	25.43
306.49	32.41	301.81	28.34
346.39	35.12	341.71	31.36
386.29	37.11	381.61	33.67
		421.51	37.04

FILM NUMBER: 062502

FUEL NUMBER: BLEND 13

NOZZLE TYPE: DDA_71

VISCOSITY, cSt: 5.37

SPECIFIC GRAVITY: .8251

FUEL TEMPERATURE, C: 36.0

FUEL FLOW, mL/1000 Stk: 98.9

INJECTION NUMBER 2		INJECTION NUMBER 3	
TIME (ms)	PENETRATION (mm)	TIME (ms)	PENETRATION (mm)
19.23	1.22	23.63	1.39
59.13	3.76	63.53	3.75
99.03	7.88	103.43	7.69
138.93	12.34	143.33	12.29
178.83	16.69	183.23	16.77
218.73	20.45	223.13	21.12
258.63	23.36	263.03	24.22
298.53	26.26	302.93	26.74
338.43	29.10	342.83	29.27
378.33	31.25	382.73	31.33
418.23	32.60	422.63	33.36
458.13	33.70	462.53	34.82
498.03	35.77	502.43	36.73

FILM NUMBER: 070901

FUEL NUMBER: DFM

NOZZLE TYPE: DDA_71

VISCOSITY, cSt: 2.96

SPECIFIC GRAVITY: .8488

FUEL TEMPERATURE, C: 37.0

FUEL FLOW, mL/1000 Stk: 99.1

INJECTION NUMBER 2		INJECTION NUMBER 3	
TIME (ms)	PENETRATION (mm)	TIME (ms)	PENETRATION (mm)
14.92	.87	17.81	.80
54.82	3.19	57.71	2.59
94.72	7.15	97.61	6.81
134.62	11.29	137.51	10.88
174.52	15.09	177.41	14.83
214.42	19.30	217.31	17.89
254.32	21.88	257.21	22.83
294.22	23.74	297.11	27.49
334.12	26.13	337.01	29.76
374.02	28.62	376.91	31.05
413.92	31.15	416.81	32.47
453.82	32.85	456.71	33.44
493.72	35.03	496.61	34.44
533.62	37.04	536.51	36.11
573.52	38.73	576.41	37.97
613.42	40.60	616.31	39.79
653.32	42.60	656.21	41.95

FILM NUMBER: 070902

FUEL NUMBER: BLEND 9

NOZZLE TYPE: DDA_71

VISCOSITY, cSt: 25.17

SPECIFIC GRAVITY: .8586

FUEL TEMPERATURE, C: 34.0

FUEL FLOW, mL/1000 Stk: 101.6

INJECTION NUMBER 2		INJECTION NUMBER 3	
TIME (ms)	PENETRATION (mm)	TIME (ms)	PENETRATION (mm)
21.47	2.00	23.17	1.64
61.37	5.72	63.07	4.45
101.27	11.19	102.97	9.68
141.17	16.78	142.87	14.28
181.07	19.95	182.77	17.35
220.97	22.51	222.67	19.49
260.87	27.18	262.57	24.72
300.77	30.19	302.47	29.24
340.67	33.01	342.37	33.90
380.57	35.33	382.27	36.75
420.47	36.76	422.17	38.60
460.37	38.97	462.07	41.01
500.27	41.00	501.97	43.15

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